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Innovations Announced in Nitride-Based Semiconductor Technology and Materials Characterization
(See MRS Proceedings Volume 743)

In Symposium L on GaN and Related Alloys, recent results on growth and characterization of III-nitride semiconductors and their application in optoelectronic and electronic devices were reported. Several advances were reported in nitride-based technology for visible and UV-light emitters. Researchers at the University of South Carolina presented results on LEDs operating at 250 nm, while NTT researchers presented 350-nm UV LEDs with maximum external efficiency of 1.4%; phosphor-coated red and white LEDs incorporating their UV LEDs were also described by NTT. Lumileds researchers discussed the performance of their latest Luxeon LEDs, which achieve external quantum efficiency of 25% and 10% at 450 nm and 530 nm, respectively. In addition, Lumileds presented a demonstration of backlighting using 34 Luxeon chips to create a full-color light source with color temperature up to 15,000 K.

A number of notable results in the nitride materials characterization arena were presented, particularly with regard to defect structure and the behavior of Mg in p-doped GaN. Continued advances were also reported in the development of nitride-based electronic devices. New materials and device designs for nitride-based heterostructure FETs, targeted for rf power applications, were presented by several research groups. Included among these was a discussion of advances in the growth and fabrication of nitride electronic devices on Si substrates. Also reported were initial results on an AlGaAs-GaAs-GaN heterostructure biopolar transistor realized using a wafer fusion process for device fabrication.

Symposium Support: AFOSR and ONR/DARPA.

SYMPOSIUM L

GaN and Related Alloys

December 2 – 6, 2002

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* Invited paper

SESSION L1: EPITAXY—DEVICES AND DEFECT REDUCTION
Chair: Russell D. Dupuis
Monday Morning, December 2, 2002
Room 302 (Hynes)

8:30 AM *L1.1
ISSUES FOR NITRIDE UV DEVICES. Hiroshi Amano, Shun Takanami, Yoshihito Tomida, Motoaki Iwaya, Shugo Nitta, Satoshi Kamiyama, Isamu Akasaki High-Tech Research Center, Meijo Univ., Tempaku-ku, Nagoya, JAPAN.

Success of nitride for blue and green light emitting diodes and violet laser diode pushes this material forward to much shorter wavelength UV region. Among several approach toward high performance UV emitter, our approach is focusing on the growth of high-quality AlGaN. Combination of low-temperature interlayer and lateral growth by grooved underlayer enabled the high-quality AlGaN on sapphire with a dislocation density as low as 108cm-2 in the whole wafer. Microscopic CL image around the dislocations suggested diffusion length of excited carriers, thus we can expect the effective luminescent area as a function of dislocation density. 80% or more of the effective area is expected for dislocation density of 108cm-2. Lattice matched metallic substrate, ZrB2, also provides a high quality AlGaN with the same dislocation density or even less. Performance of the UV devices on these low dislocation density AlGaN and factors which limits performance of the UV devices will be discussed.

9:00 AM L1.2
LARGE-AREA, DEVICE QUALITY GaN ON Si USING A NOVEL TRANSITION LAYER SCHEME. Pradeep Rajagopal, Thomas Gehrke, John C. Roberts, T. Warren Weeks, Kevin J. Linthicum, Edwin L. Piner, Nitronex Corporation, Raleigh, NC.

The emergence of III-nitride technology and fabrication of high quality GaN based devices was made possible due to the advances in the heteroepitaxial growth of III-N thin-films on lattice-mismatched substrates. Typically, the substrate of choice is either SiC or sapphire. We have adopted 100mm Si as our substrate of choice; it is plentiful, inexpensive, and high quality substrates are available due to decades of use in the microelectronics industry. Growth of device quality GaN on Si is challenged by the ~17% lattice mismatch and the additional thermal expansion coefficient mismatch. In order to accommodate this strain and thermal mismatch between Si and GaN, a novel transition layer was designed, grown and successfully optimized, obviating the need for either a Pendeo(') based overgrowth process or a SiC interlayer-based process. This direct SiGaNtic(') growth approach reduces process complexity and maintains the cost effectiveness of the GaN on Si strategy. We will report on this manufacturable 100mm MOCVD hetero-epitaxial process that consistently produces device quality AlGaN/GaN heterostructures with 2-D electron gas mobilities typically around 1400 cm^2/Vs at room temperature. Structural, electrical and optical properties as determined by atomic force microscopy, photoluminescence, capacitance-voltage, van der Pauw, and reflectance measurements, which are mapped across the 100mm wafer, will be presented. Device results will be presented to show RF continuous wave operation at 2 GHz with competitive power output, high gain and power added efficiency and exceptional linearity.

9:15 AM L1.3
REDUCTION OF STRESS AND DISLOCATIONS AT THE INITIAL STAGES OF GaN GROWTH FOR THICK (>5 μm), CRACK-FREE GaN LAYERS ON Si(111). M. Poschenrieder, A. Dadgar, J. Blaesing, F. Bertram, A. Diez, J. Christen, and A. Krost, Otto-von-Guericke Universitaet Magdeburg, Magdeburg, GERMANY; O. Contreras and F.A. Ponce, Department of Physics and Astronomy, Arizona State University, Tempe, AZ.

The growth of GaN on Si(111) is very interesting for the mass production of cheap LEDs and transistor devices. Recently several reports have shown the possibility of growing thick crack-free GaN layers for such device structures [1, 2]. But still devices suffer from a high dislocation density which can increase the series resistance of vertically contacted devices and enhance the tendency for cracking. To improve the GaN properties it has been shown [2, 3] that SiN in-situ masks are a simple, low-cost method to reduce the dislocation density. We have demonstrated that such masks significantly enhance the light output power of our LEDs [2]. To further improve the material quality such masks can be also applied directly on the AlN seed layer commonly used for GaN growth on Si. With such a masking the buffer layer growth starts in a 3d mode from few GaN seeds comparable to the growth from a GaN seed layer on sapphire. After coalescence of the layer we find a significantly enhanced luminescence of the GaN layer and a reduced tensile stress. The reduction in tensile stress around 0.3 GPa for a 700 nm thick layer can be attributed to the decrease in grain boundary density due to an increased island size. Applying such SiN masks and four LT-AlN interlayers for stress reduction [4] crack-free GaN layers in excess of 5 μm were grown on Si(111) with x-ray FWHMs of the GaN reflections of 370 arcsec (0002) and 300 arcsec (20-24). [1] E. Feltin, et al., Appl. Phys. Lett. 79, 3230 (2001) [2] A. Dadgar, et al., 2002, Appl. Phys. Lett. 80, 3670 (2002) [3] P.R. Hageman, et al., phys. stat. sol. (a) 188, 523 (2001) [4] A. Dadgar, et al., Jpn. J. Appl. Phys. 39, L1183 (2000).

9:30 AM L1.4
III-NITRIDE GROWTH ON LITHIUM NIOBATE: A NEW SUBSTRATE MATERIAL FOR POLARITY ENGINEERING IN III-NITRIDE HETEROEPITAXY. W. Alan Doolittle, Gon Namkoong, Alexander Carver and Walter Henderson, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA; April S. Brown, School of Electrical and Computer Engineering, Duke University, Durham, NC.

Herein, we present the theory and experiment supporting a new substrate that can control the polarity of III-Nitride films as well as lead to novel polarization engineered structures. Inexpensive, widely available, ferroelectric Lithium Niobate substrates was used for III-Nitride growth. The ability of this substrate to control and even spatially select the polarization of the film is an advantage over other substrates and facilitates new device structures that utilize the acoustic, non-linear optical, and ferroelectric properties of this novel substrate. Results from computer modeling of the crystalline mismatch between lithium Niobate, III-Nitrides and SiC as well as experimental validation of the computer results will be presented. GaN has been successfully grown on (0001) and (000$\bar{1}$) oriented and poled lithium niobate using plasma assisted molecular beam epitaxy and found by polarity determination etches to be Ga-polar and N-polar respectively. Reflection high energy electron diffraction patterns on the as-purchased lithium niobate showed very streaky unreconstructed surfaces with six fold symmetry indicating the surface was very smooth and the surface crystal quality was not plagued by polish damage, as can be the case for other common III-Nitride substrates. Optimal growth conditions will be discussed. Omega-two theta X-ray diffraction and reciprocal space mapping indicate alignment of the < 0001 > direction of GaN along the < 0001 > direction of lithium niobate with line widths comparable to GaN on sapphire (<275 arc-sec 0002 x-ray line widths) but with minimal mosaic tilt. Photoluminescence of the GaN silicon doped to 1e18 cm-3 shows strong exitonic emission, but also shows faint yellow band emission indicative of defects in the film. Since the polarization of lithium niobate can be selected via poling, novel polarization engineered devices can be developed containing lithographically patterned regions of Ga or N-polar nitrides. Results from attempts to grow such structures will also be discussed.

10:15 AM L1.5
DISLOCATION MOBILITY AND YIELD STRENGTH OF BULK SINGLE-CRYSTAL GaN. Ichiro Yonenaga, Institute for Materials Research, Tohoku University, Sendai, JAPAN.

Knowledge on the dynamic characteristics of dislocations and mechanical strength at elevated temperatures is crucially important as a basis in order to control of dislocation generation and plastic deformation during crystal growth and device processing and also to improve the optical and electronic performance of the material. Up to now, far less is known on the mechanical properties of III-V nitride semiconductors except on the hardness mainly at room temperature. This paper reports on the direct measurement of yield strength and the estimation of dislocation mobility in bulk single-crystal GaN at elevated temperatures in comparison with other semiconductors. Specimens prepared form bulk single-crystals wurtzite-GaN grown as free standing substrates by the HVPE technique were deformed directly by means of compressive deformation at elevated temperatures. The crystals were deformed plastically at temperatures higher than 900°C without brittle fracture under the application of extremely high compressive stress. The yield stress of GaN in the temperature range 900 ~ 1000°C is around 100 ~ 200 MPa, i.e. similar to that of 6H-SiC and much higher than those of Si and GaAs. From the analysis of the temperature dependence of the yield stress an activation energy for dislocation motion in the GaN is estimated to be 2 ~ 2.7 eV. The dislocation structure in deformed crystals will also be included.

10:30 AM L1.6
SELF-SEEDING GROWTH OF ALUMINUM NITRIDE SINGLE CRYSTALS. B. Liu, D. Zhuang, and J.H. Edgar, Kansas State Univ, Dept of Chemical Engineering, Manhattan, KS.

Transparent platelet AlN single crystals up to 60mm^2 were grown by the sublimation recondensation technique. Hot pressed boron nitride crucibles were employed, as it was very durable, had good nucleation characteristics, and produced pure, stress-free crystals. Platelets were generally produced at high growth temperatures (above 2100°C), in temperature gradients below 10°C/cm, and longer growth times (>24

hours). The AlN single crystal platelets from free nucleation were used as seeds for later on seeded growth. The growth behavior was investigated when the AlN single crystals from free nucleation and on-substrates growth were employed as seed. The growth rate was anisotropic, the relationship between the orientation of the seed and the growth direction was discussed as well. The fastest growth rate coincided in the crystallography [100] direction when needle shaped crystals were used as seeds, while it was along the crystallography [001] for platelet seeds. The defect density of the crystals as determined by synchrotron white beam topography was on the order of 10^5 cm^{-2}.

10:45 AM L1.7
SUBLIMATION GROWTH OF BULK AlN CRYSTALS.
Rafael Dalmau, Raoul Schlesser, Zlatko Sitar, North Carolina State University, Dept of Materials Science and Engineering, Raleigh, NC.

AlN bulk single crystals were grown by sublimation of AlN powder at temperatures of 2100 - 2300 C in a 400 Torr nitrogen atmosphere. Growth experiments were carried out under quasi-stagnant flow conditions, with typical flow rates of 100 sccm, employing a variety of crucible materials such as BN, W, Ta and TaN. The growth morphology of spontaneously nucleated crystals was found to depend on the temperature gradient between the source and crystal and on the crucible material. Growth experiments that used BN crucibles in temperature gradients below 2 C/mm produced thin, striped plates with the growth direction along the crystallographic c-axis, while in temperature gradients of 2-5 C/mm, c-platelets were formed. These c-plates grew at rates of 1-4 mm/hr in the c-plane and 0.1 mm/hr along the c-axis. All grown single crystals were transparent and virtually colorless. Refractory metal crucibles of W and TaN yielded well faceted, coalesced crystalline deposits characterized by a deep orange color. Seeded growth was demonstrated in all crucibles, and crystal size was seen to linearly increase with time. Crystal quality was analyzed by a range of techniques, including surface imaging techniques, x-ray topography, TEM, cathodoluminescence, and SIMS. Thermal conductivity measurements were performed on c-plates. Analytical results indicated very high crystalline quality and purity of colorless crystals.

11:00 AM L1.8
CANTILEVER EPITAXY OF GaN ON SAPPHIRE: FURTHER REDUCTIONS IN DISLOCATION DENSITY. D.M. Follstaedt, P.P. Provencio, D.D. Koleske, C.C. Mitchell, A.A. Allerman, N.A. Missert and C.I.H. Ashby, Sandia National Laboratories, Albuquerque, NM.

Low densities of vertical threading dislocations (VTDs) in GaN are important for improving device performance. To reduce VTDs in heteroepitaxial GaN, lateral growth methods were developed. Of these, cantilever epitaxy (CE) has the advantages of requiring a single growth step and avoiding contact with barrier layers. If all VTDs remained vertical, the density would be reduced by the ratio of the width of the mesa used to seed GaN growth to the total width of cantilever + mesa, or ~1/7 for our substrate pattern. We have used two methods to reduce VTD density further for GaN on sapphire. First, we grow on mesas <~1 um wide, since we have seen VTDs near mesa edges turn to horizontal. Second, we form slanted facets during initial growth over the mesas; VTDs intersecting these facets turn to horizontal. Using substrates with narrow mesas extending in the [1-100] direction, we have done a detailed comparison of VTDs in CE-GaN grown with a) initial vertical {11-20} sidewalls, or b) slanted {11-22} facets. Growth was done by MOCVD, with a 25nm AlN nucleation layer at 480C and initial vertical growth at either a) 1050C, or b) 950C, followed by cantilever growth at 1100C. Cross-section TEM showed that for a), 30-70% of VTDS were unturned and threaded to the surface. For b), this percentage was lower and even 0% for mesas narrow enough to be completely covered by the facets. Plan-view TEM and scanning cathodoluminescence showed that for b) the average density of VTDs at the surface was reduced to 3-8x10^7/cm^2, or ~1/40 that of planar growth. We have developed a GaN nucleation procedure that reduces VTD density in planar growth; when applied to narrow mesas along with the faceting growth step, a VTD density of 2-3x10^7/cm^2 was achieved.

11:15 AM L1.9
LATERAL GROWTH OF AlGaN AND GaN ON SiC SUBSTRATES PATTERNED BY PHOTO-ELECTROCHEMICAL ETCHING. U. Rossow, N. Riedel, F. Hitzel, T. Riedl, and A. Hangleiter Institute of Technical Physics, Technical University of Braunschweig, GERMANY.

The large defect densities associated with heteroepitaxial growth of nitrides are detrimental particularly to laser diodes. Well-known lateral growth schemes such as epitaxial lateral overgrowth (ELOG) rely on overgrowth of pre-deposited nitride layers. However, due to the tensile strain developing as a consequence of thermal contraction after cool-down, the maximum possible layer thickness on SiC substrates severely limits application of such schemes. In order to limit the layer thickness as much as possible, we have developed a patterning process for n-type doped SiC substrates based on photoelectrochemical (PEC) etching. Stripe patterns aligned along either $(1\bar{1}00)$ or $(11\bar{2}0)$ and periods between 5 and 10 microns were etched to depths between 0.5 and 2 microns. Low-pressure metal-organic vapor phase epitaxy (MOVPE) in a horizontal reactor was then used to grow Si-doped AlGaN/GaN layers on the patterned 6H-SiC substrates under conditions of large lateral growth rates, yielding fully coalesced layers for stripes oriented along $(1\bar{1}00)$. Characterization of the layers using photo-electrochemical (PEC) etching as well as near-field microscopy (SNOM) utilizing the GaN band-edge emission was performed, which are both sensitive to nonradiative defects. A strong reduction of the threading defect density in the laterally grown regions by at least one order of magnitude was confirmed. The PEC etching analysis also revealed defect lines propagating parallel to the layer plane, which indicates that dislocations lines are oriented along the lateral growth direction as expected.

11:30 AM L1.10
MASS TRANSPORT AND KINETIC LIMITATIONS IN GaN EPITAXIAL LATERAL OVERGROWTH. Michael E. Coltrin and Christine C. Mitchell, Sandia National Laboratories, Albuquerque, NM.

The interplay between transport and kinetics in Epitaxial Lateral Overgrowth (ELO) of GaN is discussed. A thin-film model describing transport of reactants across the boundary layer above the growth surface is developed. A dimensionless Damkohler number (Da) quantitatively determines whether the planar (blanket) deposition is in a transport-limited, reaction-rate-limited, or intermediate operating regime. Reactant profiles within the rotating-disk reactor and growth rates predicted by the thin-film model agree very well with numerically exact calculations. The efficiency of the ELO was found to be a strong function of both the Damkohler number and the pattern fill-factor (θ). The thin-film model was extended to take into account the lowering of the "effective rate constant" (averaged over both the exposed and masked zones). It was found that the product θDa governs the transition between transport and kinetic control of the ELO process. Predictions of the analytical ELO thin-film model were compared to both the numerically exact 2-D calculations and to GaN experimental results. The simple theory appears to provide an excellent qualitative and quantitative description of kinetic and transport effects in Epitaxial Lateral Overgrowth. *Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

11:45 AM L1.11
THE NATURE OF MAGNESIUM PRECIPITATION IN GaN AND AlGaN DEPOSITED BY EPITAXIAL LATERAL OVERGROWTH. R. Liu, A. Bell, F.A. Ponce, D. Cherns[a], H. Amano[b] and I. Akasaki[b], Dept. Physics and Astronomy, Arizona State University, Tempe, AZ; [a]H.H. Wills Physics Laboratory, Bristol, UNITED KINGDOM; [b]Dept. Materials Science and Eng., Meijo University, Nagoya, JAPAN.

Mg segregation in group-III nitrides can have a detrimental effect on the p-type electrical conductivity in high-performance devices. In this work, transmission electron microscopy (TEM) has been used to study Mg segregation in AlGaN and GaN doped with high levels of magnesium. $Al_0.03Ga_0.97N$ and GaN samples were grown by metal-organic chemical vapor deposition using epitaxial lateral overgrowth (ELO) on a stripe-patterned grooved sapphire substrate. Cross-sectional TEM images of these ELO Mg-doped samples show two distinct regions associated with different Mg segregation behavior; one includes triangle-shaped Mg precipitates (with hexagonal shape on the basal plane), and the other is uniform and free of these defects. The nature of the microstructure appears to depend on the orientation of the growth surface. In the case of ELO, one growth front is perpendicular to the c-axis, while the lateral front follows an inclined $\{11-22\}$ facet. The former is definitely associated with the formation of triangular precipitates, while the latter does not exhibit precipitation and instead has highly homogeneous properties. Suggested by its distinct incorporation mechanism in the ELO domains, the Mg impurity appears to work like a surfactant, promoting lateral growth on the inclined $\{11-22\}$ nitride facet, but reducing the vertical growth rate on the $\{0001\}$ facet. This would explain the widely observed lateral overgrowth enhancement due to Mg-doping. In addition to forming hexagonal-pyramidal-shape precipitates, Mg segregation has been observed to occur preferentially along dislocations with edge components in AlGaN. In the vicinity of edge-type dislocations, the density of Mg precipitates is highly reduced because the compressive strain fields around edge dislocations getter some of the dopant. The optical properties of these samples have been studied using cathodoluminescence microscopy and spectroscopy to correlate with the TEM analysis. The Mg segregation mechanisms revealed by this work are important for producing Mg-doped nitrides with higher optical and electrical properties.

SESSION L2: DEFECTS AND CHARACTERIZATION
Chair: Ed T. Yu
Monday Afternoon, December 2, 2002
Room 302 (Hynes)

1:30 PM *L2.1
FIRST-PRINCIPLES TOTAL ENERGY CALCULATIONS FOR NITRIDE MATERIALS: SURFACES AND DISLOCATIONS.
John E. Northrup, Palo Alto Research Center, Palo Alto, CA.

Total energy and electronic structure calculations will be discussed for surfaces and dislocations in GaN. Our interest in these topics arises from their importance for understanding epitaxial growth and optoelectronic properties of the material. I will discuss the structure of the GaN(0001) surface and its dependence on the growth stoichiometry, which is described in terms of the chemical potentials of the constituents. In the Ga-rich limit, where surface reconstructions would be in equilibrium with large Ga droplets, the lowest energy surface reconstruction that has been obtained is the laterally contracted Ga bilayer structure. The existence of this structure is important for understanding growth. I will also discuss the atomic and electronic structure of screw dislocations and how the equilibrium structure depends on the chemical potential. In the Ga-rich limit the lowest energy structure has a core filled with Ga atoms. This core structure gives rise to a large number of states in the gap and is a source of non-radiative recombination.

2:00 PM L2.2
EVIDENCE FOR A NEW DISLOCATION TYPE IN GaN. L. Lymperakis, J. Neugebauer, Fritz-Haber-Institut, Berlin, GERMANY; T. Remmele, M. Albrecht, H.P. Strunk, Universität Erlangen, GERMANY.

Despite a large body of theoretical and experimental work the question whether dislocations in GaN are recombination active is still controversially discussed. Previous theoretical studies [1] calculated structure and electronic properties of four different core structures of this dislocation (full core, Ga vacancy, N vacancy, open core) and found that all variants are electrically active. In contrast a number of experimental studies find a-type dislocations to be not active. The question appears whether this is due to passivation of the dislocation core by H or due to a new type of dislocation core. Based on first-principles total energy calculations we propose a new type of a reconstructed dislocation core (having a 4-ring structure) for the a-type dislocation. In contrast to the previous core structures the new structure cannot be obtained by just adding/removing atoms from the core but it involves also a small shift between the lattice planes. Evidence for this core structure is found from a through focus high resolution transmission electron microscopy study in samples grown by hydride vapour phase epitaxy. Based on the different ab initio calculated geometries of the core structure image simulations are performed by multi-slice calculations. The best fit between simulated and experimental images is obtained for the reconstructed 4-ring structure. Cathodoluminescence performed in the TEM confirms that these dislocations are not recombination active. [1] A. Wright, U. Grossner, Appl. Phys. Lett. **73**, 2751 (1998).

2:15 PM L2.3
DETERMINATION OF THE ELECTRICAL CHARGE STATE OF THREADING DISLOCATIONS IN GALLIUM NITRIDE BY SCANNING SURFACE POTENTIAL MICROSCOPY.
André Krtschil, Armin Dadgar, and Alois Krost, Institute of Experimental Physics, Otto-von-Guericke-University Magdeburg, Magdeburg, GERMANY.

Due to their omnipresence in epitaxial layers dislocations are one of the most interesting topics in the field of the group III-nitrides. Especially, the discussion on their electrical impact is quite controverse originated by a lot of conflicting results in the literature. In this paper, we present scanning surface potential microscopy (SSPM) analysis of differently doped n- and p-type GaN layers grown by metalorganic vapor phase epitaxy on c-axis oriented sapphire substrates. The aim of our study is to get information on the charge state of threading dislocations, which result in surface depressions around their intersections at the surface, for a wide variety of GaN layers. Interestingly, we observe systematic differences in the charge of dislocation-related pits depending on layer doping. Typically, these pits are negatively charged in Mg-doped and in some nominally undoped GaN layers, but they are electrically nonactive in Si-doped and in other undoped layers. This behaviour will be discussed with respect to a possible dependence on the Fermi level position and in the context of decoration effects with other defects. Based on these results, we present a model to determine the effective coulomb charge of the dislocations by analyzing the SSPM-signal as a function of distinct scan parameters. Thus, we find a different amount of coulomb charge for the distinct types of dislocations which will be discussed in detail. Furthermore, we will present first results from optically induced scanning surface potential microscopy measurements (OSSPM) at dislocations, i.e. SSPM investigations in conjunction with monochromatic light excitation, which are intended to reveal the optical transition energies of the dislocation-related deep levels or of the corresponding decoration defect states, respectively.

2:30 PM L2.4
CORRELATED SCANNING KELVIN PROBE AND CONDUCTIVE ATOMIC FORCE MICROSCOPY STUDIES OF DISLOCATIONS IN GALLIUM NITRIDE. B.S. Simpkins, University of California, San Diego, Materials Science Program, San Diego, CA; E.T. Yu, University of California, San Diego, Dept of Electrical and Computer Engineering, San Diego, CA; P. Waltereit, University of California, Santa Barbara, Dept of Materials, Santa Barbara, CA; J.S. Speck, University of California, Santa Barbara, Dept of Materials, Santa Barbara, CA.

Threading dislocations in GaN can degrade device performance through carrier scattering[1], non-radiative recombination[2], and increased reverse-bias leakage current[3]. However, the correlation among dislocation type, electronic properties such as charge and conductivity, and corresponding effects on device performance remain subjects of active investigation. Correlating these device degradation mechanisms with specific dislocation types will determine which dislocation types are most harmful to device performance and will help to more fully characterize these threading dislocations in GaN. In this study, scanning Kelvin probe microscopy (SKPM) and conductive atomic force microscopy (C-AFM) have been used to image surfaces of GaN grown by MBE on MOCVD templates deposited on sapphire substrates. By imaging the same area using both techniques, both surface potential variations arising from the presence of negatively charged threading dislocations and localized leakage paths associated with dislocations can be imaged. Correlations between the charge state of dislocations, conductivity of leakage current paths, and possibly dislocation type can thereby be established. Analysis of correlated SKPM and C-AFM images reveals a density of negatively charged dislocations of $\sim 7 \times 10^{7} cm^{-2}$ and a localized leakage path density of $\sim 2 \times 10^{7} cm^{-2}$ with approximately 25% of the leakage paths spatially correlated with negatively charged dislocation features. Previously, Wu et al reported that ~70% of dislocations in MOCVD GaN were of pure edge character leaving the remainder as pure screw and mixed[4]. Since GaN grown by MBE on MOCVD templates is expected to retain the dislocation types and concentrations of the template, our results suggest that dislocations having an edge component behave as though negatively charged and dislocations having a screw component act as leakage paths. A small subset of dislocations, (5-6%), presumably of mixed character, exhibits both negative charge and leakage current. 1 H.M. Ng, D, Doppalapudi, T.D. Moustakas, N.G. Weimann, and L.F. Eastman, Appl. Phys. Lett. 73, 821 (1998). 2 T. Sugahara, H. Sato, M. Hao, Y. Naoi, S. Tottori, K. Yamashita, K. Nishino, L.T. Romano, and S. Sakai, Jpn. J. Appl. Phys. 37, L398 (1998). 3 E.J. Miller, D.M. Schaadt, and E.T. Yu,. to appear in J. Appl. Phys. (2002). 4 X.H. Wu, L.M. Brown, D. Kapolnek, S. Keller, S.P. Denbaars, and J.S. Speck, J. Appl. Phys. 80, 3228 (1996).

2:45 PM L2.5
THE CORE STRUCTURE OF DISLOCATIONS IN GALLIUM NITRIDE GROWN UNDER Ga-RICH AND Ga-LEAN CONDITIONS. Marcus Q. Baines, David Cherns, Bristol Univ, Dept of Physics, Bristol, UNITED KINGDOM; Julia W.P. Hsu, Michael J. Manfra, Bell Labs, Lucent Technologies, Murray Hill, NJ.

There is great interest in the formation mechanism of hollow core dislocations in GaN films. Previous work has shown that screw dislocations can be hollow core with diameters around 5-25nm [ref: Cherns et al, J CRYST GROWTH 178 (1-2): 201-206 JUN 1997]. In addition, the density of such defects, or nanopipes, can be correlated with the presence of impurities (e.g. O) and dopants (e.g. Si) [ref: Liliental-Weber, Z, J. Electron Microscopy 49 (2): 339-348 2000]. This paper examines the influence of the Ga-N ratio on dislocation structure. Transmission electron microscopy (TEM) studies have been used to compare dislocations in GaN films grown by MBE under Ga-rich and Ga-lean conditions, on a HVPE GaN template on a sapphire substrate. Studies on both plan-view and cross-sectional samples showed that dislocations with an edge component of Burgers vector had different core structures. In Ga-rich material, the dislocation cores were often extended. This was particularly clear in plan view samples, where dislocations, when viewed end-on, showed hollow cores with typically 5nm diameter. In some cases, these cores are coated with amorphous material, believed to be Ga-rich from preliminary studies using energy dispersive X-ray microanalysis (EDX). In contrast, studies of Ga-lean material showed that the dislocations were predominantly closed core, although often associated with pronounced surface pits. Higher resolution studies of the dislocation core structure and chemistry are currently being carried out, and will be reported at the meeting.

3:30 PM *L2.6
PROPERTIES AND PASSIVATION OF ELECTRONIC STATES AT FREE SURFACES AND SCHOTTKY INTERFACES OF GaN AND RELATED ALLOYS. Hideki Hasegawa and T. Hashizume, Research Center for Integrated Quantum Electronics (RCIQE) and Graduate School of Electronics and Information Engineering, Hokkaido University, Sapporo, JAPAN.

GaN-based electronic devices suffer presently from various surface/interface-related problems such as current collapse, large gate leakage currents etc. Their understanding and control are vitally important for future progress.
In this paper, results of our recent efforts to clarify and control the properties of surfaces of GaN and AlGaN are presented and discussed. In addition to standard I-V-T, C-V, PL and XPS techniques, new characterization techniques developed by us have been used. They include a UHV contactless C-V technique, gateless FET technique, PL surface state spectroscopy technique and cathodoluminescence in-depth spectroscopy (CLIS) technique.
The measurements on free surfaces of GaN and AlGaN have indicated presence of high-density surface states that are characterized by a U-shaped continuous density distribution and a particular charge neutrality level. Superposed on this, near-surface deep donor discrete states have been frequently detected. On the other hand, CLIS measurements have indicated that so-called yellow luminescence is due to deep acceptors in the GaN bulk. Detailed I-V-T measurements have revealed anomalous behavior of GaN and AlGaN Schottky contacts showing extremely large reverse currents. The behavior has been explained quantitatively by a new thin surface barrier (TSB) model where observed near surface deep donors produce TSB regions of current path through thermionic-field emission mechanism. Various evidences indicate that near-surface deep donors are related to N-vacancies enhanced by high-energy processing such as metal deposition. Combining free surface and Schottky interface results, a new model for current collapse has been proposed where injections of high energy electrons from the channel into the free surface region fills up near-surface deep donors, expands the depletion width and reduces 2DEG density. Reasonably good surface passivation for this have been achieved by ECR-plasma deposited SiNx film and by ECR-plasma oxidized Al_2O_3 films where pre-passivation surface treatment by nitrogen plasma has been found very effective.

4:00 PM L2.7
ELECTRONIC STATES, MICROSTRUCTURE, AND SURFACE CHEMISTRY OF AMMONIA CLEANED GaN (0001). William J. Mecouch, T.E. Cook, P.J. Hartlieb, Z.J. Reitmeier, J.R. DiMaio, R.F. Davis, North Carolina State University, Dept of Materials Science and Engineering, Raleigh, NC; R.J. Nemanich, North Carolina State University, Dept of Physics, Raleigh, NC.

The surface of Si-doped, n-type GaN (0001) films have been studied after chemical vapor cleaning (CVC) and vacuum annealing steps. In-situ x-ray and ultraviolet photoelectron spectroscopy were used to study chemical composition, electronic states, and electron affinity, while atomic force microscopy was used to investigate changes in surface morphology during processing. The CVC clean with ammonia at 865C resulted in a surface with 3.0% O and no detectable C, an electron affinity of 2.9±0.2 eV, and upward band bending of 0.4±0.2 eV. AFM after one CVC shows a smooth surface with unit cell terraces. After the CVC, the sample was heated in vacuum to 700C, 715C, and 830C, with in-situ analysis conducted between each anneal. The oxygen concentration changed with each anneal, increasing to 6.8%, then to 8.4%, then decreasing to 5.9%. The electron affinity increased to 4.4 eV after the first anneal, remained unchanged after the second, and then decreased to 3.2 eV after the third. Band bending was unchanged until the third anneal, when it increased to 0.7 eV upward. The UPS spectrum recorded after annealing to 830C showed surface states at the valence band maximum. A subsequent ammonia CVC process reduced the oxygen concentration to 2.7% and returned the original electron affinity of 3.0 eV. The AFM image after these processing steps showed degradation of the surface and no terraces. The data is examined to determine if ammonia or hydrogen remain adsorbed on the GaN surface after the CVC process.

4:15 PM L2.8
EFFECT OF UV ILLUMINATION AND BIAS STRESS ON SURFACE BARRIER IN AlGaN/GaN HETEROSTRUCTURES. G. Koley, Ho-Young Cha, V. Tilak, L.F. Eastman and M.G. Spencer, Cornell University, Department of Electrical and Computer Engineering, Ithaca, NY.

Large variations in surface barrier of AlGaN/GaN heterostructures caused by UV illumination and high bias stresses have been measured by Scanning Kelvin probe technique. The photogenerated carriers created by UV illumination screen the electric field across the AlGaN layer lowering the surface barrier (by as much as 1 eV) and increasing the two-dimensional electron gas (2DEG) density at the interface. After UV illumination, the surface barrier recovers slowly over a period of few days to a few weeks. The recovery transient is modeled by thermionic emission of electrons from the 2DEG, which recombines with the trapped holes at the surface. It becomes faster at higher temperatures and slower for higher Al composition in the barrier layer. The surface barrier height estimated from the transient measurements is ~1.6 eV for 35% Al composition in the barrier layer. Spatially localized surface potential variation can be patterned on a heterostructure sample by exposing it through a quartz mask. In opposition to UV induced reduction, a huge increase (few eV) in surface barrier can be observed after application of large biases to the gate and drain of an AlGaN/GaN heterostructure field effect transistor for a few minutes. Simultaneous measurements of surface potential and surface morphology up to 1 micron from the gate edge reveals that the changes mostly occur within 0.5 - 0.6 micron from the gate edge towards the drain side. It is proposed that electrons tunnel from the gate under high bias stress and get trapped at the surface states near the gate causing such an increase in surface barrier. This increase in surface barrier reduces the 2DEG, as inferred from simultaneous measurement of surface potential and drain current recovery transients after stressing a device for a few minutes. Silicon nitride passivation reduces the transient magnitudes while UV illumination eliminates the transients altogether as the photogenerated holes neutralize the trapped electrons.

4:30 PM L2.9
AN ATTEMPT TO CORRELATE MACROSCOPIC TRANSPORT PARAMETERS OF GaN LAYERS TO THEIR LOCAL ELECTRICAL PROPERTIES IN SUBMICRON SCALE. H. Witte, A. Krtschil, E. Schrenk, K. Flügge, A. Dadgar, A. Krost, J. Christen, Otto-von-Guericke-Universität Magdeburg, Institute of Experimental Physics, Magdeburg, GERMANY.

Transport parameters such as carrier mobility or carrier concentration are typical key features of semiconductors for device applications. However, little is known on the impact of the electrical microstructure of the layers, i.e. the influence of interfaces or lateral fluctuations of sur-face potential on these macroscopic parameters. In this paper we present an approach to get more information on this interaction. Several nominally undoped and Si-doped GaN layers grown by metal organic vapor phase epitaxy on c-sapphire substrates were investigated by temperature dependent Hall effect (TDH), by transient and spectral dependent photo-Hall effect (PHE), as well as by conductivity and photoconductivity measurements with respect to their transport properties. The results are correlated to electrostatic force microscopy (EFM) and scanning surface potential microscopy (SSPM) measurements in plane view and cross sectional configuration with a spatial resolution of about 20 nm. In plane view analysis of the GaN top layer, we can distinguish three groups of samples with different behavior in PHE, i.e. a decrease, an increase or an unchanged photo-induced carrier concentration. These groups also differ in the lateral variation of the surface potential in SSPM resulting in a reduction of the carrier mobility due to dominant scattering processes at these laterally distributed potential barriers. Furthermore we found differences in photo-induced capture and emission processes in PHE, which are discussed in terms of these potential barriers. Micro cracks within the layers are found to be responsible for the very low carrier mobility and for strong fluctuations during the Hall effect measurements. Furthermore, EFM and SSPM measurements were performed after a dimple or a bevel preparation providing information on the electrical microstructure of the interface layer. In some cases a conductive interface layer with a gradual transition to the GaN top film was observed which controls the carrier concentration at low temperatures.

4:45 PM L2.10
SPATIAL VARIATION OF TRANSCONDUCTANCE IN AlGaN/GaN HETEROSTRUCTURES IMAGED BY SCANNING GATE MICROSCOPY. J.W.P. Hsu, N.G. Weimann, M.J. Manfra, K.W. West, Bell Labs, Lucent Technologies, Murray Hill, NJ; D.V. Lang, Agere Systems, Berkeley Heights, NJ; R.J. Molnar, MIT Lincoln Lab, Lexington, MA.

Scanning gate microscopy (SGM) uses the conducting probe of an atomic force microscope as a local gate to modulate the conductance of the 2DEG between source and drain. To map transconductance variation, a dc bias, V_{DS}, is applied between drain and source while both a dc and an ac bias, $V_{GS}+V_{ac}\cos(\omega t)$, are applied between the tip (gate) and source. The ac component of the current between drain and source, I_{DS}, is measured using a lock-in amplifier at frequency ω. Transconductance is defined as $\Delta I_{DS}(\omega)$ {/ V_{ac}. The AlGaN/GaN heterostructures were grown by molecular beam epitaxy on semi-insulating GaN template prepared by hydride vapor phase epitaxy. The gateless transistor structures used in the SGM experiments are mesas, made next to and with ohmic contacts made in the same processes as conventional HEMTs. The potential drop

between the drain and source was mapped using scanning Kelvin force microscopy and found to be linear. Preliminary results show that near the surface, the transconductance variation correlates with surface morphology and is probably due to non-uniformity in AlGaN thickness. Near depletion of the 2DEG, transconductance show cell like structures. Beyond the depletion of the 2DEG, transconductance signals indicate trapping in the HVPE templates. SGM study of different device structures as well as devices fabricated on different substrates will be discussed.

SESSION L3: POSTER SESSION
Monday Evening, December 2, 2002
8:00 PM
Exhibition Hall D (Hynes)

L3.1
EARLY STAGES OF GaN GROWTH ON AlN NUCLEATION LAYERS GROWN ON (0001) SAPPHIRE BY METALORGANIC CHEMICAL VAPOR DEPOSITION. Vijay Narayanan, IBM T.J. Watson Research Center, Yorktown Heights, NY; Mario Gonsalves, Wook Kim, Subhash Mahajan, Dept of Chemical and Materials Engineering, Arizona State University, Tempe, AZ.

The early stages of high temperature (HT) GaN growth on low temperature AlN nucleation layers (NLs) deposited on (0001) sapphire have been investigated by transmission electron microscopy (TEM). Plan-view micrographs of as-deposited AlN NLs (10 nm) grown at 530°C and 100 mbar indicate the presence of 2-3 nm wurtzitic regions. The micrographs also show distorted and irregular moiré which may be indicative of strain within these films. Upon annealing to the growth temperature (1030°C), plan-view and cross-sectional images do not exhibit any microstructural changes. Diffraction patterns from as-deposited and annealed AlN NLs show distinct horizontal spot splitting of $< 11\bar{2}0 >$ AlN reflections. HT GaN growths on the annealed AlN NLs nucleate as flat topped, distorted hexagonal islands that grow epitaxially on AlN NLs. In addition, black-white regions are observed in cross-sections of the AlN/sapphire interface. Plan-view images of HT GaN at different stages of growth and coalescence show clear evidence of coalescence boundaries and absence of threading dislocations (TDs) at these boundaries. Cross-sectional micrographs of the HT GaN growths indicate the presence of black-white bands at the coalescence of islands. In addition, TEM images show a high density of basal plane dislocations and TDs attached to these dislocations. Arguments will be developed to rationalize these observations. Acknowledgements: The authors would like to gratefully acknowledge the support of this work by AFOSR

L3.2
INFLUENCE OF PRESSURE ON THE GROWTH MECHANISM AT THE EARLY STAGES OF THE MOCVD GROWTH OF GaN THIN FILMS. Seong-Woo Kim, Tomoki Shibata, Toshimasa Suzuki, Nippon Inst. of Technology, Saitama, JAPAN; Takashi Yamada, Kazuhiro Haga, Chichibu Fuji Co. Ltd, Saitama, JAPAN.

Elucidation of the growth mechanism of group-III nitride thin films is very important to obtain device quality epitaxial layers. We have observed the early stages of the epitaxial growth and the transition from three-dimensional (3D) to two-dimensional (2D) growth of GaN films grown under different pressure by metalorganic chemical vapor deposition (MOCVD) on sapphire substrates.
The growth of GaN films was performed in an ECORE D-125 multi-wafer rotating disc low-pressure MOCVD system. All nucleation layers (NL) were grown and heat-treated under the same conditions. The thickness and the growth pressure of NL were 30nm and 200Torr, respectively. Just after heating up and starting high-temperature epitaxial growth, the reactor pressure was changed to 100Torr, 300Torr or fixed at 200Torr. The film growth was interrupted at each stage, quenched to room temperature and took out from the reactor. First we observed the condition of lateral growth and coalescence by atomic force microscopy (AFM). It showed the tendency that the higher the growth pressure was, the larger the trapezoid crystals grew. AFM observation also showed the change of the density of islands, i.e. the higher the growth pressure was, the smaller the density of islands became.
Then we observed rather thick GaN films (up to 2μm thick) by scanning laser microscopy (SLM). It showed corresponding tendency to AFM results, i.e. the higher the growth pressure was, the larger features were observed by SLM. We concluded that the features observed by SLM reflect the transition layer from 3D to 2D growth mode, i.e. overall structure of the trapezoid crystals observed through two-dimensionally grown sound-zone layers.

L3.3
INFLUENCE OF THE SAPPHIRE NITRIDATION CONDITIONS ON GaN FILMS GROWN BY CYCLIC-PLD. P. Sanguino, M. Niehus, S.V. Koynov, L.V. Melo, R. Schwarz, Instituto Superior Técnico, Dept of Physics, Lisboa, PORTUGAL; T. Monteiro, M.J. Soares; Aveiro University, Dept of Physics, Aveiro, PORTUGAL; H. Alves, B.K. Meyer, Justus-Liebig University, Dept of Physics, Giessen, GERMANY.

Recently, we have deposited highly c-axis oriented GaN films on sapphire by the Cyclic Pulsed Laser Deposition Technique [1]. Although the deposition process is not completely optimised, our latest deposited films already show a broad (200 meV at 14K) near band edge (NBE) photoluminescence peaked ca. 3,47 eV. The ratio of the NBE to yellow luminescence was 16 for our best films. These, were deposited in sapphire substrates at a deposition temperature of 650°C. The type of luminescence (YL or NBE) proofed to be extremely dependent on deposition temperature and laser spot location. Nitridation of the sapphire substrates for these samples was performed at 800°C for 30 minutes with the help of a 1mbar/8W r.f. Nitrogen plasma. Quality of the nitridation layer is crucial for the reduction of structural defects and consequently increase of NBE/YL ratio. In this work, we investigate the influence of temperature, N2 pressure, plasma power and duration of the sapphire nitridation process on the growth of GaN films. For this study, typical deposition temperatures range from 500°C to 700°C. The GaN samples thus obtained are compared in terms of optical and structural quality. Photoluminescence, uv-visible transmission spectra, x-ray diffraction and atomic force microscopy are the techniques used to characterise and compare the deposited films in order to determine the ideal nitidation conditions. [1] P. Sanguino, M. Niehus, S. Koynov, L. Melo, R. Schwarz, T. Monteiro, M. J. Soares, H. Alves, B. K. Meyer, Characterisation of GaN Films Grown on Sapphire by Low Temperature Cyclic Pulsed Laser Deposition/Nitrogen RF, presented at E-MRS Spring Meeting (2002), Strasbourg, France. To be published in Solid State Electronics.

L3.4
STUDY ON CHEMICAL TREATMENT AND HIGH TEMPERATURE NITRIDATION OF SAPPHIRE FOR III-NITRIDE HETEROEPITAXIAL GROWTH. F. Dwikusuma, T.F. Kuech, Department of Chemical Engineering, University of Wisconsin, Madison, WI; D. Saulys, Materials Research Science and Engineering Center, University of Wisconsin, Madison, WI.

The surface preparation of sapphire for III-nitride heteroepitaxial growth remains a critical consideration for improvement of the epitaxial film quality. Prior to growth, the chemical treatment of sapphire has been used to remove polishing damage and the surface nitridation has been used to improved film nucleation. We have systematically studied the effects of wet chemical etching and high temperature nitridation on the resulting sapphire surface morphology and chemical transformation. The etching of c-plane sapphire substrates using H_2SO_4, H_3PO_4, and a 3:1 H_2SO_4:H_3PO_4 mixture as a function of temperature and etching time was studied and compared with H_2 etching at 1100°C and air-annealing at 1400°C. The surface nitridation using NH_3 at 1100°C was studied as a function of NH_3 concentration, nitridation time, and surface pretreatment. Atomic force microscopy and x-ray photoelectron spectroscopy were used to study the surface morphology and chemical composition. The sapphire etching rate and detailed morphological result of the chemical etching was a function of the chemical composition and the specific time and temperatures used in the treatment. The smoothest, pit-free sapphire surface was obtained by etching in pure H_2SO_4 at 300°C for 30 min. Sulfuric acid etching at higher temperatures or for longer periods generated an insoluble mixture of $Al_2(SO_4)_3$ and $Al_2(SO_4)_3 \cdot 17H_2O$ crystalline deposits on the surface. Phosphoric acid and the 3:1 H_2SO_4:H_3PO_4 mixture, which is the routinely employed chemical treatment for sapphire preparation, etched the sapphire preferentially at defect sites and resulted in pits formation on the surface. The sapphire nitridation resulted in nitrogen incorporation into the surface forming a mixture of AlN and NO species. The chemical composition of nitridation layer strongly depends on NH_3 concentration, nitridation time, and surface pretreatment. No protrusions were observed on the sapphire surface for nitridation up to 60 min.

L3.5
ION BEAM STUDY OF EARLY STAGES OF GROWTH OF GaN FILMS ON SAPPHIRE. Eugen M. Trifan, David C. Ingram, Department of Physics and Astronomy, Ohio University, Athens, OH.

The composition, growth mode, morphology and crystalline ordering of the early stages of growth of GaN films on sapphire have been investigated for substrate temperatures in the range of 450 to 1050C. We have used in-situ characterization by Rutherford Back Scattering Spectroscopy, X-ray Photoelectron Spectroscopy, and Low Energy Electron Diffraction. The films have been grown by MOCVD using TMGa and ammonia as precursors and the growth conditions have been optimized. From LEED patterns and Channeling we have determined the crystallographic phase to be wurtzite and the XPS

analysis indicates surface contamination by O and C and also some carbon incorporation in the film. The RBS analysis indicated that the films have variable thickness and for low substrate temperature completely cover the substrate while for temperatures 850C and higher islands are formed that may cover as few as 5 percent of the substrate. The channeling results indicate a better crystalline quality with higher deposition temperature and for thicker films. The channeling shows that the c crystallographic axis and planes of the GaN films are aligned with the sapphire substrate within 0.2 degrees. The study shows that in the early stages of growth, the crystalline ordering, growth mode and morphology of GaN films are strongly influenced by the substrate temperature and deposition conditions and Ion Beam techniques can be used to characterize the film quality. Good epitaxial films were grown at 950C with a minimum yield corresponding to single crystals.

L3.6
REAL-TIME OPTICAL MONITORING OF GAS PHASE KINETICS IN InN VAPOR PHASE EPITAXY AT HIGH PRESSURE. Nikolaus Dietz, Vincent Woods, Georgia State University, Department of Physics, Atlanta, GA.

Understanding the kinetics of nucleation and coalescence of heteroepitaxial thin films is a crucial step in controlling a chemical vapor deposition process, since it defines the perfection of the heteroepitaxial film both in terms of extended defect formation and chemical integrity of the interface. The initial nucleation process also defines the film quality during the later stages of film growth. The growth of emerging advanced material heterostructures such as InN or indium-rich GaxIn1-xN requires deposition methods operating at high vapor densities due to the high thermal decomposition pressure in these materials. High nitrogen pressure has been demonstrated to suppress thermal decomposition of InN, but has not yet been applied in chemical vapor deposition experiments. The extension of chemical vapor deposition (CVD) to elevated pressure is also necessary for retaining stoichiometric single phase surface composition for materials that are characterized by large thermal decomposition pressures at optimum processing temperatures. The here presented research focuses on the base material InN and addresses the real-time optical monitoring of gas phase- and surface chemistry processes during high pressure CVD of InN. For this we constructed a high pressure CVD reactor with integrated optical diagnostics to monitor in real-time gas flow dynamics, gas-phase decomposition kinetics, and the film growth process itself. These experimental data are of crucial importance to provide (a) input parameter for process models and simulation codes, and (b) establish growth parameter sets needed for analysis and control of chemical vapor deposition at elevated pressure. First data are presented for the optical methods of real-time process monitoring such as precursor flow conditions to analyze the initial stages of heteroepitaxy and steady-state growth in the different pressure ranges.

L3.7
LOW TEMPERATURE LASER-ASSISTED GAS PHASE REACTIVITY OF TMAl AND TMGa WITH NH_3 AND OXYGEN-CONTAINING COMPOUNDS (H_2O, $HO(CH_3)$, $O(CH_3)_2$) IN CONSTRAINED PULSE EXPANSIONS. Alexander Demchuk, APA Optics, Inc, Blaine, MN; Michael Lynch, Steven Simpson and Brent Koplitz, Dept of Chemistry, Tulane University, New Orleans, LA.

The present work reports on our efforts involving cluster formation that combine pulsed laser photolysis and pulsed nozzles in order to growth III-V clusters, in particular GaN and AlN, from metalorganic precursors. The experimental apparatus consists of a high vacuum chamber (base pressure $\sim 10^{-7}$ Torr) equipped with a quadrupole mass spectrometer (QMS) and a specialized multipulsed gas source nozzle assembly. Ammonia and oxygen-containing compounds (water, methanol, and dimethylether) are transiently mixed by pulsed nozzles with various metalorganic compounds: trimethylgallium (TMGa), triethylgallium (TEGa), or trimethylaluminum (TMAl). As a gas mixture passes toward the vacuum chamber, it is exposed to a nanosecond light pulse from an ArF excimer laser (λ=193 nm) whose output is focused into the mixing and reaction region of the source nozzle assembly. The products are then mass analyzed with a QMS. The efficient laser-assisted growth of GaN and AlN containing clusters is demonstrated, and the influence of gas pressures and laser energy as well as nozzle temperature and oxygen-containing impurities on the cluster formation is presented.

L3.8
HIGH-MOBILITY Ga-POLARITY GaN ACHIEVED BY NH_3-MBE. Junxi Wang, Xiaoliang Wang, Dianzhao Sun, Jinmin Li, Yiping Zeng, Guoxin Hu, Hongxin Liu, Lanying Lin, Institute of Semiconductors, Chinese Academy of Sciences, Beijing, P.R.CHINA.

The polarity of GaN has become a hot topic due to its crucial influence on both material quality and device performance in recent years. Commonly GaN epilayers have two possible polarities, Ga-polarity and N-polarity. GaN with Ga-polarity is usually desired because it has smoother surface of GaN epilayer and better 2DEG properties of HEMT device. But with molecular beam epitaxy (MBE), the growth mechanism of Ga-polarity films is not clear and Ga-polarity films are not easy to obtain, which hampers the development of GaN based devices. In this letter, we studied the polarity of the GaN films grown on (0001) sapphire by NH_3-MBE. We found that the key method to achieve Ga-polarity GaN film was substrate nitridation by NH_3 and an AlN buffer grown at high temperature using radio frequency activated N as N source. Both of them needed to realize the polarity control. As a result, not only Ga-polarity films can be easily and stably obtained but also the electron mobility of the Ga-polarity film is significantly improved with a best value higher than most GaN material grown by MBE. The mechanism of polarity control and mobility improvement is also discussed. The experiments were carried out on a homemade MBE system with two growth chambers equipped with in situ RHEEDs. One growth chamber was designed for NH_3-MBE using ammonia as N source and the other was for RF-MBE using radio frequency activated N as N source. Polarity identification was performed first by chemical solution etching and followed by AFM surface examination. KOH aqueous solution with concentration of 1:1 was used as etchant to dissolve GaN epilayer at room temperature. Surface morphology of as-grown and etched film was investigated by a contacting-mode Digital Instrument Nanoscope IIIa AFM equipment. All Ga-polarity films were further confirmed by RHEED patterns.

L3.9
PHASE TRANSITIONS ON GaN SURFACES. Christoph Adelmann, Julien Brault, Guido Mula, Bruno Daudin, CEA-Grenoble, Equipe mixte CEA-CNRS-UJF Nanostructures et Semiconducteurs, Grenoble, FRANCE; Liverios Lymperakis, Joerg Neugebauer, Fritz-Haber-Institut, Berlin, GERMANY.

Recent experimental and theoretical studies highlighted the importance of the growing surface structure on the final morphology of GaN. Actually, optimum morphology is achieved by growth in presence of a Ga bilayer adsorbed on the GaN surface. The threshold fluxes limiting the region of the Ga bilayer adsorption have been measured as a function of the GaN substrate temperature, giving rise to a Ga adsorption phase diagram. The results are in qualitative agreement with recent results of B. Heying et al.[1], although exhibiting puzzling differences: Studying GaN epitaxial growth Heying *et al.* find for an activation barrier of 2.8 eV and a prefactor of $3.3*10^{13}$ nm s^{-1} for the transition from Ga-bilayer structure to Ga droplet formation. However, measuring the adsorption phase diagram (i.e. no GaN growth) an activation barrier of 5.1 eV and a prefactor of 10^{25} s^{-1} have been found [2]. These results pose a number of questions: First, why are the activation energies and prefactors so different? Second, what is the physical meaning of a prefactor of $10^{25...26}$ s^{-1}? These questions were adressed by studying the adsorption/desorption of Ga adatoms and small islands (consisting of 2 and 3 Ga adatoms) on the Ga bilayer surface employing first principle density functional theory calculations. We find a desorption barrier of 2.1 eV and a binding energy between two Ga atoms of $\approx$ 0.3 eV. Using these numbers we derived a simple growth model (based on rate equations). An analysis of the experimental data with the model revealed the origin of the large difference in the activation energies and the unusually large prefactor. We find that the nucleation of the droplets cannot be described by a simple Arrhenius behavior (as commonly assumed to fit experimental data) but that the nucleation energy is temperature dependent.
[1] B. Heying et al., J. Appl. Phys. 88, 1855 (2000).
[2] C. Adelmann *et al.*, J. Appl. Phys. (in press, 06/01/2002).}

L3.10
NITROGEN GAS-CLUSTER ION BEAM-A NEW NITROGEN SOURCE FOR GaN GROWTH. Y. Shao, D.B. Fenner, Epion Corporation of JDS Uniphase, Billerica, MA; T.C. Chen, T.D. Moustakas, Boston Univ, Dept. of Electrical & Computer Eng., Boston, MA.

In MOCVD and MBE GaN growth, active nitrogen is produced by thermal decomposition of ammonia or plasma activation of molecular nitrogen. We report the growth of GaN using ionized nitrogen clusters as a nitrogen source. Nitrogen clusters are formed by adiabatic expansion and condensation of compressed nitrogen gas through a small nozzle into vacuum. The clusters are nominally singly ionized, nanoscale droplets, that are accelerated to 10-25 kV, and disintegrate upon impact with the substrate surface, where they and react with Ga atoms to form GaN. From time-of-flight and RGA measurements it was found that the nitrogen clusters have a wide size distribution with $< M/Q > \sim$2000-3000 (atoms/charge), and the cluster break-up fragments contain not only N_2 but also N_n for n=16. The efficiency of this novel nitrogen source was tested first by studying the nitridation of (0001) sapphire substrates at relatively low temperatures of 200 to

400°C. The effect of exposure of the substrate to the nitrogen cluster-ion beam was examined by XPS, RHEED and AFM. The peak observed at 396.8 eV in the XPS spectra corresponds to Al-N bonds. It was found that the amount of retained surface nitrogen increases nonlinearly with increasing beam energy. There exists a threshold of about ~20 kV above which nitrogen retention is significantly enhanced. This is consistent with the expected N2 cracking energy and thus activation of molecular nitrogen by the cluster impact. GaN films were grown with nitrogen clusters heteroepitaxially on sapphire with MBE-grown AlN buffer, and homoepitaxially on thick GaN, HVPE grown on sapphire. The films were characterized by SEM, TEM and room-temperature CL measurements. The heteroepitaxial GaN showed defect density in TEM similar to that of MBE and MOCVD grown films. The homoepitaxially-grown GaN was found to replicate the GaN templates and show strong CL emission at 363 nm with FWHM of 9 nm. Furthermore, the spectra show no evidence of yellow band emission.

L3.11
GROWTH OF THIN ORIENTED GALLIUM NITRIDE FILMS ON AMORPHOUS SUBSTRATES USING SELF ASSEMBLY.
M.K. Sunkara and H. Li, Department of Chemical Engineering, University of Louisville, Louisville, KY.

Nitrogenated gallium melt flows on any substrate that it comes in contact with. The nucleation and growth of gallium nitride crystals from the flowing nitrogenated gallium melt will allow for self-assembly and intra-platelet orientation. This is expected due to the alignment of platelet shaped crystals with their longest dimensions parallel to flow direction. Utilizing this phenomena, we were able to grow thin films of c-plane textured gallium nitride on amorphous substrates. Thin gallium films were initially spin-coated onto amorphous quartz substrates and then subjected to nitrogen plasma. In some experiments, the flow from large gallium droplets under nitrogen plasma exposure also produced similar results. The plasma was generated using microwaves at the electron cyclotron resonance frequency (MW ECR). The deposition occurred at substrate temperatures ranging from 850 - 1050C. Resulting films were approx. 0.25 - 1 m thick over a 2" diameter area. The resulting films were characterized using Raman Spectroscopy, X-Ray Diffraction, PL Spectroscopy, UV-Vis Spectroscopy, cross-sectional Transmission Electron Microscopy and Atomic Force Microscopy. Both cubic and hexagonal gallium nitride films were obtained and were highly textured. By repeating thin film nitridation over the same substrate, the thickness of the textured gallium nitride films increased. Current work is focused on experiments with a 2 in. quartz substrate placed on a heated substrate stage that rotates at speeds greater than 2000 rpm. This project is sponsored by AFOSR under DEPSCoR program and is partially supported by a CAREER grant from National Science Foundation.

L3.12
RAMAN MAPPING AND FINITE ELEMENT ANALYSIS OF EPITAXIAL LATERAL OVERGROWN GaN ON SAPPHIRE SUBSTRATES.
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Micro-Raman scattering and finite element (FE) analysis were used to investigate stress fields in epitaxial lateral overgrown (ELO) GaN and double epitaxial lateral overgrown (D-ELO) GaN grown by metalorganic vapor phase epitaxy (MOCVD) on sapphire substrates. Reductions in stress variations at the D-ELO top surface with respect to single ELO GaN were achieved. Stress near the top surface was mainly attributed to the presence of voids on top of the upper dielectric mask.Also spatial variations in crystalline quality and free carrier concentration in the ELO GaN were investigated.

L3.13
STRAIN DISTRIBUTION IN EPITAXIAL LATERALLY-OVERGROWN GaN ON HEXAGONAL MASK.
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The epitaxial laterally overgrown (ELOG) GaN sample is grown by hydrogen vapor phase epitaxy (HVPE) on a SiO_2 mask on top of a GaN buffer. Unlike the most common masks used that has stripe patterns, the mask in our sample has a pattern of hexagons. Combining cross-sectional imaging at cleaved faces perpendicular to the c-axis and depth-resolved cathodoluminescence (CL), we could establish a three dimensional mapping of the luminescence. Also, micro-Raman spectroscopy parallel to the c-axis has been carried out at different depths of the sample. LPP modes can be distinguished in comparison to quasi-LPP modes observed in in-plane measurements. We correlate the informations on local strain and free-carrier distribution deduced from Raman sppectroscopy with the CL wavelength images. We use a three dimensional finite-element application of the elasticity theory to simulate the strain distribution in the sample. We make use of the theoretical results in the discussion of luminescence shifts in different domains in the sample that we expect are the combined effect of strain and impurities.

L3.14
A CRYSTAL PLASTICITY MODEL FOR THE LATERAL EPITAXIAL OVERGROWTH OF GaN.
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Lateral epitaxial overgrowth (LEO) GaN provides an interesting modeling system to study dislocation density evolution because of the two distinct regions that are composed of high and low dislocation density accumulations that are associated with the vertical and lateral growth of GaN. Analytical description of the dislocation density evolution law and computational methodologies [1] have been developed and used to characterize the effect of dislocation reaction mechanisms, interfacial stress and strain evolutions, and slip-system orientations on the deformation in LEO GaN structure. Deformation modes of lateral epitaxial overgrowth of GaN on 6H-SiC layered systems also have been investigated. The total dislocation density distribution is proposed as a function of time and deformation histories and it is coupled to known experimental results in conjunction, with specialized finite-element computational techniques. Interfacial stresses and thermal evolution as a function of slip system orientations were monitored and obtained during the deformation history on physical scales commensurate with LEO GaN. It is shown that these computational methodologies can be used as design guidelines to determine optimal architectures for LEO GaN systems.
[1] Ashmawi, W. M, and Zikry, M. A. (2000), Effects of grain boundaries and dislocation density evolution on large strain deformation modes in fcc crystalline materials, Journal of Computer-Aided Materials Design, 7 (1): 55-62.

L3.15
COMPARISON OF LATERAL DEFECTS IN CANTILEVER EPITAXIAL GaN ON SAPPHIRE.
P.P. Provencio, D.M. Follstaedt, N.A. Missert, D.D. Koleske, C.C. Mitchell, A.A. Allerman, and C.I.H. Ashby, Sandia National Laboratories, Albuquerque, NM.

Cantilever epitaxy (CE) was developed to reduce vertical threading dislocations (VTDs) by growing GaN laterally over large areas without contact with to a surface. With CE, sapphire is etched to a mesa/well configuration. GaN nucleates on the mesas, and is grown first vertically and then laterally by changing the growth conditions. CE has a significant advantage over other lateral growth techniques in that it requires only a single growth. Using substrates with narrow mesas (<1 um) extending in the [1-100] direction, we have compared CE-GaN microstructures for two different vertical growths: 1) at 1050C for nearly parallel {11-20} sidewalls, and 2) at 950C for slanted {11-22} facets. The MOCVD growth temperature is increased to 1100C for lateral growth of the cantilevers. Both TEM and scanning cathodoluminescence showed that facetted growth was more efficient in reducing VTDs; the average density of VTDs was reduced to as low as $2\text{-}3x10^7/cm^2$. Here, we focus on the microstructural differences between the two types of growth. Growth with the parallel {11-20} sidewalls results in tilting of the cantilevers with respect to the mesas, giving a dark/light diffraction contrast. Using electron diffraction patterns, the tilts were measured as approximately a degree between the mesas and the cantilevers. This tilting is produced by lateral dislocations extending along the mesa edges. Lateral GaN growth on the slanted {11-22} facets produced large areas with no measurable tilting; however, high densities of horizontal dislocations do occur in isolated regions. These isolated regions appear dark in scanning cathodoluminescence, and are likely non-radiative recombination centers similar to the VTDs in planar GaN. Many of the regions contain a vertical crack parallel to the mesas, with dislocations bowing out laterally from it. These regions are being studied to understand their origin and to eliminate them in CE GaN growth.

L3.16
InGaN/GaN MULTIPLE QUANTUM WELL LEDS GROWN BY MOCVD USING CANTILEVER EPITAXY.
A.J. Fischer, D.D. Koleske, A.A. Allerman, C.C. Mitchell, K.H.A. Bogart, R.J. Shul, J.J. Figiel, K.W. Fullmer, Sandia National Laboratories, Albuquerque, NM.

Vertical threading dislocations (VTD) in GaN are known to be

non-radiative recombination centers and are therefore detrimental to LED efficiency. Lateral overgrowth techniques have enabled dramatic reductions in VTD densities with $<10^6$ cm^{-2} achievable in the overgrown wing regions. Cantilever epitaxy distinguishes itself from other overgrowth techniques in that it requires only one MOCVD growth run and has the potential to reduce dislocations over the post region as well as the wing region, which is particularly important for large area devices such as LEDs. For cantilever epitaxy (CE), GaN growth is nucleated on top of stripes that have been etched out of the substrate (such as sapphire, SiC or Si). GaN growth eventually extends laterally over the etched trench until growth fronts from adjacent stripes coalesce. LEDs were grown using CE which had an overall VTD density of 2×10^8 cm^{-2} as measured by AFM. After nucleation on the sapphire posts and coalescence of the wings, a 2 μm thick Si-doped GaN layer was grown followed by a 20 nm thick Si:AlGaN layer (4%). The active region consisted of five periods of a 4 nm thick InGaN (4%) quantum well with 10 nm thick GaN barriers. Si doping (1×10^{18} cm^{-2}) was used in the barriers to reduce the piezoelectric field and enhance overlap of electron and hole wavefunctions. The structure was completed with a 20 nm thick Mg:AlGaN (10%) confinement layer followed by a 250 nm thick Mg:GaN contact layer. An output power of 1.3 mW at 391 nm was measured at 20 mA from LED's grown on a fully coalesced CE-GaN film. Sandia is a multiprogram laboratory operated by Sandia Corporation, for the United States Department of Energy under Contract DE-ACO4-94AL85000.

L3.17
STUDY OF THE ORIGIN OF MISORIENTATION IN GaN GROWN BY PENDEO-EPITAXY. Dmitri N. Zakharov, Zuzanna Liliental-Weber, Lawrence Berkeley National Laboratory, Materials Sciences Division, Berkeley, CA; Sven Einfeldt, University of Bremen, Institute of Solid State Physics, Bremen, GERMANY; Robert F. Davis, North Carolina State University, Department of Materials Science and Engineering, Raleigh, NC.

In order to investigate the origin of misorientation in GaN grown on 6H-SiC (0001) substrates by pendeo-epitaxy a set of samples from different growth stages has been studied by Transmission Electron Microscopy. First, a 1 μm thick plane GaN layer on an AlN buffer layer was investigated. Second, a corresponding layer which was etched into stripes to permit pendeo-epitaxial growth was studied. Third, the latter samples were annealed for 10 min at 1000 $^{(}_{0})$C which is equivalent to the growth temperature used for pendeo-epitaxy. The as-grown GaN layer revealed the presence of pure screw and pure edge threading dislocations with the dislocation density $\sim 5.4 \times 10^8$ cm^{-2} near the surface of the film and 1.9×10^9 cm^{-2} close to the interface with the substrate. Etching of stripes did not change the type of defects or their distribution. However, heating to pendeo-epitaxy growth temperature drastically modified the surface, which became very rough with a peak-to-valley roughness of $\sim$150 nm. Therefore in the samples, where pendeo-epitaxy took place, the surface was rough prior to growth, but became smooth after growth suggesting that during growth the V-shaped 'valleys' were completely or partially filled in. This apparently resulted in formation of some c-plane dislocation lines and some of them may propagate into the upper part of the pendeo grown material leading to the increase of the dislocation density to 1.7×10^9 cm^{-2}. If these edge dislocations lying on or near the c-plane are predominantly of one sign in one local region and predominantly of the opposite sign in an adjacent region they will cause local misorientation in the upper part of the pendeo grown regions.

L3.18
DISLOCATION REDUCTION IN HETEROEPITAXIAL NONPOLAR $(11\bar{2}0)$ A-PLANE GaN FILMS VIA LATERAL OVERGROWTH. Michael D. Craven, Sung-Hwan Lim, Feng Wu, James S. Speck, Steven P. DenBaars, Materials Department, University of California, Santa Barbara, CA.

Polarization in wurtzite III-nitride compounds has attracted increased attention due to the large effect of polarization-induced electric fields on nitride-based optoelectronic and electronic devices. Current state-of-the-art nitride devices are subject to polarization effects since the polar c-axis coincides with the predominant growth direction of these device structures. A promising means of eliminating the effects of these internal fields is through the growth of nitride structures in nonpolar directions (perpendicular to the GaN c-axis). The research presented here examines the microstructure of heteroepitaxial nonpolar GaN films and the dislocation reduction achieved with subsequent lateral overgrowth. Initially, the structural characteristics of nonpolar $(11\bar{2}0)$ a-plane GaN films grown on $(1\bar{1}02)$ r-plane sapphire substrates via metalorganic chemical vapor deposition were analyzed. Planar growth surfaces were achieved and the potential for device-quality layers realized by depositing a low temperature nucleation layer prior to the high temperature epitaxial growth. The in-plane orientation of the GaN with respect to the r-plane sapphire substrate was determined to be $[0001]_{GaN}$ // $[\bar{1}101]_{sapphire}$ and $[\bar{1}100]_{GaN}$ // $[11\bar{2}0]_{sapphire}$ using x-ray and convergent beam electron diffraction techniques. Threading dislocations (TDs) and stacking faults, as observed in transmission electron micrographs, dominated the a-plane GaN microstructure with densities of 2.6×10^{10} cm^{-2} and 3.8×10^5 cm^{-1} respectively. Despite the successful growth of planar nonpolar GaN films, defect densities must be reduced for eventual "polarization-free" device layer growth. TD density reduction was achieved via lateral epitaxial overgrowth (LEO) from mask stripe openings aligned along $[\bar{1}100]_{GaN}$. For all other stripe orientations, TDs were observed to propagate into the overgrown regions. In addition to the stripe orientation dependence of dislocation reduction and LEO stripe morphology, the effects of polarity on a-plane GaN lateral overgrowth will be discussed.

L3.19
EFFECT OF GROWTH CONDITIONS ON THE NUCLEATION OF HIGH TEMPERATURE GaN ISLANDS GROWN BY MOCVD ON $\{11\bar{2}0\}$ SAPPHIRE. Frederic Degave, Pierre Ruterana, Gerard Nouet, ISMRA CRISMAT ESCTM, Caen, FRANCE; D.D. Koleske, M.E. Twigg, R.L. Henry, A.E. Wickenden, Naval Research Lab, Washington, DC.

For the last decade, GaN and related compounds have led to a great interest due to the development of applications such as high brightness light emitting diodes and laser diodes operating in the blue/green to ultraviolet range. Significant progress has been achieved in the growth process of GaN. Thin films are mostly grown by metalorganic chemical vapour deposition on basal plane sapphire despite its large lattice parameters and thermal coefficient mismatch. However, relatively little information has been reported about the growth mechanisms of GaN on $\{11\bar{2}0\}$ sapphire. In this work, the evolution of morphology and defect structure in GaN thin films on $\{11\bar{2}0\}$ plane of sapphire is investigated using optical and transmission electron microscopy. It is shown that the density of high temperature GaN islands, coalescence mechanisms and subsequently the associated defects may be directly controlled by tailoring the growth conditions.

L3.20
STRUCTURAL CHARACTERIZATION OF GaN FILMS GROWN ALONG THE NON-POLAR [11-20] DIRECTION. David J. Smith, M.R. McCartney, Arizona State University, Center for Solid State Science, Tempe, AZ; S. Iyer, A. Battacharyya, K. Ludwig, T.D. Moustakas, Boston University, Department of Electrical Engineering, Boston, MA.

GaN films and related nitride devices are generally grown along the polar [0001] direction. Different nucleation steps have been developed to facilitate the heteroepitaxial growth of GaN on (0001) sapphire substrates. These include nitridation of the substrate and the deposition of low temperature GaN and/or AlN buffer layers. Epitaxial growth along non-polar directions has attracted much less attention even though it might be anticipated that the GaN epitaxy would be affected by the polarization fields, which lie in the epitaxial plane. We report here on the growth and microstructure of GaN films and GaN/AlGaN MQWs deposited on R-plane sapphire substrates. All GaN films were grown by plasma-assisted molecular-beam epitaxy at a temperature of 750°C and growth rates of about 0.6 micron/hr. AlN and GaN buffer layers, as well as deposition without any buffer layer, were used. Overall film quality was assessed by electron mobility measurements as well as X-ray diffraction, and photoluminescence, cathodoluminescence and transmission electron microscopy were used to determine and compare the local defect microstructure. Cross-sectional electron microscopy revealed high concentrations of dislocations close to the substrate, as well as threading defects extending through the entire GaN film. Electron diffraction indicated reduced angular spread for films grown with GaN or no buffer layer, consistent with the much improved electrical and luminescence properties.

L3.21
EPITAXIAL GROWTH OF AlN ON 6H-SiC $(11\bar{2}0)$ BY MOLECULAR-BEAM EPITAXY. Norio Onojima, Jun Suda, Hiroyuki Matsunami, Kyoto Univ, Dept of Electronic Science and Engineering, Kyoto, JAPAN.

Epitaxial growth of group-III nitrides on SiC is commonly carried out on SiC (0001) substrates. SiC (0001) substrates, however, contain pinholes or micropipes running along the (0001) axis. These micropipes usually penetrate the entire crystal, and they tend to be replicated from the substrates into epitaxial layers.[1] Thus, micropipes have been recognized as a particularly serious problem for reliable device performance. In this point of view, micropipe-free substrates with the $(11\bar{2}0)$ face, which is parallel to the (0001) direction, are very attractive. If a micropipe-free SiC substrate is applied for group-III nitrides/SiC systems, more reliable device performance can be expected. In addition, exploring a new crystal

face is very important to extend the design of device structure, and to develop new functional devices. In this study, growth of AlN on 6H-SiC ($11\bar{2}0$) substrates has been performed by molecular-beam epitaxy (MBE) using elemental Al and radio frequency (rf) plasma-excited nitrogen (N*). AlN layers were grown at 1000°C in 10^{-5} Torr. Total thickness of AlN layers ranged from 0.4 to 1.0 μm. The surface roughness of AlN grown layers was relatively small (root-mean-square (RMS) roughness 0.98 nm). From the results of *in-situ* reflection of high-energy electron diffraction (RHEED) and x-ray diffraction (XRD), AlN layers grown on 6H-SiC ($11\bar{2}0$) substrates were revealed to be epitaxially grown along the [$11\bar{2}0$] direction. In addition, the epitaxial relationship between AlN and 6H-SiC was identical, i.e., $[11\bar{2}0]_{AlN}//[11\bar{2}0]_{SiC}$ and $[0001]_{AlN}//[0001]_{SiC}$. From the results of microscopic Raman scattering spectroscopy, the stacking structure of AlN ($11\bar{2}0$) grown layer was found to be wurtzite (2H) structure. Elongated surface defects expanded along the [$1\bar{1}00$] direction were observed, which will be discussed in detail. [1] D.G. Ebling, M. Rattunde, L. Steinke, K.W. Benz and A. Winnacker: J. Cryst. Growth **201/202** (1999) 411.

L3.22
GaN GROWN ON Si (111), Si (100) AND SOI SUBSTRATES. Junxi Wang, Xiaoliang Wang, Dianzhao Sun, Jinmin Li, Yiping Zeng, Hongxin Liu, Fengyi Huang, Lanying Lin, Institute of Semiconductors, Chinese Academy of Sciences, Beijing, P.R. CHINA.

The growth of nitrides on silicon is of great interesting in recent years due to the advantages of silicon, such as low cost and large-scale availability with high quality. The nitride-based LED and HEMT devices fabricated on silicon already have been demonstrated, but the large lattice mismatch and the difference in thermal expansion coefficients between GaN and silicon were still the main obstacles for materials and devices. In this letter, we grew GaN on three different substrates, Si (111), Si (100) and SOI (Si on insulator, Si overlay was about 50 nm) by ammonia (NH_3) MBE. The qualities of the grown films on three substrates with thickness of 1 μm were compared. It is well know that the crack formed on GaN surface caused by large strain is a disadvantage on Si substrate. We observed very much crack on GaN film grown on Si (111) substrate and less crack on GaN film grown on Si (100) substrate. But for GaN film grown on compliant substrate, SOI, we found it was crack-free. AFM (atom force microscope) surface observation showed that the GaN film grown on SOI substrate was mirror-like with a RMS (root mean square) of 0.6 nm, and the same value of GaN films grown on Si (111) and Si (100) substrates are 5 nm and 10 nm, respectively. XRD (x-ray diffraction spectroscopy) and TEM (transmission electronic microscope) analyze results were also discussed in the letter. Obtained results show that the compliant substrate can release strain and absorb threading dislocations, so it was suitable for the growth of GaN-based materials.

L3.23
ELECTRICAL PROPERTIES OF GaN/Si GROWN BY MOCVD. Seikoh Yoshida, Jiang Li, Takahiro Wada and Hironari Takehara, Yokohama R&D Laboratories, The Furukawa Electric Co., Ltd, Nishi-ku, Yokohama, JAPAN.

GaN and related materials are very important for high power, high frequency, and high temperature electronic devices. Recently, GaN epitaxial growth on Si substrate has been actively studied for realizing low cost electronic devices. In this power, we report on the GaN/Si epitaxial growth and its Schottky diode and FET properties. We grew the GaN on p type Si (111) substrate using an AlGaN high temperature buffer without using a conventional low temperature buffer. At first, we investigated the formation condition of a thin AlGaN buffer layer on the Si (111) substrate at different growth temperatures. A homogenous buffer layer was obtained at 820°C and a homogenous 0.8~1.0 μm thick GaN layer was also obtained without cracking in a two inch wafer. Using a transmission electron microscope (TEM), we observed that the interface of GaN and AlGaN buffer was very smooth and the surface of GaN was also flat. The Hall mobility of undoped GaN was about 300 cm^2/Vs and the carrier concentration was $5x10^{16}$ cm^{-3} at room temperature. Furthermore, we fabricated a Schottky diode using a GaN/Si. A Schottky electrode was Pt/Au and an ohmic electrode was Al/Ti/Au. A Schottky reverse breakdown voltage (V_R) was over 100 V. A forward voltage (V_F) was about 0.3 V. Also, we confirmed the current-voltage property of FET using this GaN/Si. Therefore, it was thus confirmed that a GaN grown on an AlGaN high temperature buffer are very effective for electronic devices.

L3.24
STUDIES ON EPITAXIAL RELATIONSHIP AND INTERFACE STRUCTURE OF AlN/Si(111) AND GaN/Si(111) HETEROSTRUCTURES. T. Rawdanowicz, H. Wang, A. Kvit, and J. Narayan, Department of Materials Science and Engineering, North Carolina State University, Raleigh, NC.

We present the details of epitaxial growth interface structure of single crystal wurtzite AlN thin films on (111) Si substrates by laser-molecular-beam-epitaxy. High-quality AlN thin films with atomically sharp interfaces can be obtained by Laser-MBE at a substrate temperature of 750± 10°C. X-ray diffraction and high resolution transmission electron microscopy was used to study the details of epitaxial growth of AlN on Si(111) substrate. The orientation-relationship of AlN on Si(111) was studied from Si $< 110 >$ and $< 112 >$ zone axes and determined to be AlN [$2\bar{1}\bar{1}0$] || Si[110] and AlN [$01\bar{1}0$] || Si[112]. The atomic structure of the interface and the nature of dislocations at the two interfaces were studied by high-resolution transmission electron microscopy and Fourier filtered image of cross-sectional AlN/Si(111) samples from both Si $< 110 >$ and $< 112 >$ zone axes. The results revealed the domain matching epitaxy of 4:5 ratio between the interplanar distances of Si (110) and AlN ($2\bar{1}\bar{1}0$). We also present similarities and differences between the growth mechanism of AlN/Si(111) and GaN/Si(111) heterostructures.

L3.25
CORRELATION BETWEEN THE AlN BUFFER LAYER THICKNESS AND THE GaN POLARITY IN GaN/AlN/Si(111) GROWN BY MBE. A.M. Sanchez, P. Ruterana, ESCTM-CRISMAT, UMR6508-CNRS, ISMRA, Caen, FRANCE; S.I. Molina, F.J. Pacheco, R. Garcia, Dept de Ciencia de los Materiales e I. M. y Q. I., Universidad de Cadiz, Puerto Real, SPAIN; F. Calle, T.A. Palacios, M.A. Sanchez-Garcia, E. Calleja, Dept de Ingenieria Electronica, ETSI Telecomunicacion, UPM, Madrid, SPAIN.

An intense research in nitride based III-V materials is being carried out due to the wide range of practical applications of these semiconductors, and the understanding is rapidly progressing. Nevertheless, the knowledge of heterostructures based on GaN grown over sapphire has considerably advanced, in contrast the GaN heteroepitaxy growth on Si(111) has received less attention. As the extended defects may reduce the device efficiency, a high structural quality of the epilayer is required. Moreover, the film polarity is an important factor in the device performance. A change from N-polarity to Ga-polarity has been determined when the AlN thickness increases, nevertheless inversion domains reaching the GaN surface have been observed in both polarities [1]. Studies carried out in order to determine the inversion domain origin in the GaN/AlN/Si(111) concluded the existence of two possible factors: the substrate steps and the AlN buffer layer [2]. In this work we analyze the main geometric factors for the inversion domain generation by High Resolution Transmission Electron Microscopy (HRTEM) on cross sectional specimen. Thin AlN buffer layers cause N-polarity GaN epilayers, with inversion domains originating from the substrate surface. When the AlN thickness increases, the GaN overgrown epilayer has an absolute polarity mainly type Ga. The AlN misorientated subgrains in the buffer layer lead to the inversion domain generation in the GaN. These results point to the achievement of Ga-polarity layers by increasing the AlN buffer layer thickness like in GaN/AlN/sapphire, where an AlN buffer layer with a thickness of 50 nm leads to avoid the inversion domains generation, and formation of a Ga-polarity epilayer. [1] A.M. Sanchez, F.J. Pacheco, S.I. Molina, P. Ruterana, F. Calle, T.A. Palacios, M.A. Sanchez-Garcia, E. Calleja and R. Garcia, Mat. Sci. Eng. B 93 (2002) 181 [2] A.M. Sanchez, P. Ruterana, S.I. Molina, F.J. Pacheco and R. Garcia, submitted to Phys. Stat. Sol.

L3.26
SINGLE CRYSTALLINE InN FILMS GROWN ON Si SUBSTRATES BY USING A BRIEF SUBSTRATE NITRIDATION PROCESS. Tomohiro Yamaguchi, Kazuhiro Mizuo, Yoshiki Saito, Takuma Noguchi, Tsutomu Araki, Yasushi Nanishi, Ritsumeikan Univ, Dept of Photonics, Shiga, JAPAN.

InN has a large potential for photonic and electronic applications and attract much attention very recently. InN has been grown mostly on sapphire, but the lattice mismatch for Si is much smaller than that for sapphire. However, nitridation often causes amorphous SiN_x to form on Si substrate and thus prevents InN growth.[1] As a consequence of this difficulty, InN films grown on Si substrates are generally polytype. In this paper, we describe how we used nitridation to grow purely single crystalline hexagonal InN films on Si substrates.
InN films were grown on Si (111) substrates by radio-frequency plasma-excited molecular beam epitaxy (RF-MBE). A brief substrate nitridation (BSN) process was done at 800°C prior to growth. InN films were then grown at 390°C for 1 h. For comparison, InN films were also directly grown without nitridation. Film thicknesses were ~250 nm. Substrate surfaces prior to growth were observed using X-ray photoemission spectroscopy (XPS). The InN films during growth were monitored using in-situ reflection high-energy electron diffraction (RHEED).
Before nitridation, the surface had a clear (7×7) RHEED pattern. But after substrate nitridation for 3 min, the (7×7) pattern changed to (1×1). The in-plane surface lattice value measured from the

RHEED streak interval was nearly constant. However, XPS measurements showed that a SiN_x layer formed on the Si substrate surface. But RHEED pattern suggested that the SiN_x layer has not become amorphous.
InN films grown directly on Si substrates were always polycrystalline. On the other hand, single crystalline InN films were grown on the substrates with the BSN process. We have also observed the peak at ~0.8 eV in the PL spectrum at 77K. Therefore, the BSN process is a useful process to obtain high quality single crystalline InN films.
[1] A. Yamamoto et al, J. Cryst. Growth 137 (1994) 415.

L3.27
STUDY ON CUBIC GaN GROWTH ON (001) RUTILE TiO_2 SUBSTRATES BY ECR-MBE. Tsutomu Araki, Hisashi Mamiya, Ken Kitamura, Yasushi Nanishi, Faculty of Science and Engineering, Ritsumeikan Univ., Shiga, JAPAN.

Cubic GaN (c-GaN) has an advantage in fabrication of a laser diode with cleaved mirrors. It is also expected to have better electrical properties resulting from its reduced phonon scattering in higher crystallographic symmetry and smaller effective masses than hexagonal GaN. With these advantages as a background, a large number of studies to obtain c-GaN have been carried out to date. Most of these studies have used substrates with cubic crystal structure such as GaAs, 3C-SiC and Si. It has been difficult, however, to grow high quality c-GaN because of the large mismatch with the substrates and the lack of enough stability at growth temperatures. In this study, we propose the use of a (001) rutile TiO_2 substrate to grow c-GaN. For the first time, c-GaN epitaxialy grown on this substrate was obtained. GaN layers were grown by ECR-MBE. The (001) rutile TiO_2 substrate has body-centered tetragonal structure. The in-plane mismatch with (001) c-GaN is only -1.6%. The growth temperature was varied from 590°C to 710°C. Nitrogen flow rates, microwave power and Ga cell temperatures were kept constant at 30sccm, 120 W and 790°C, respectively, throughout this study. When the GaN layers were grown under 600°C or over 700°C, ring patterns were obtained in RHEED observations after the growth. This means that polycrystalline GaN was obtained at these growth temperatures. On the other hand, spot patterns were observed from the GaN layers grown at 620 - 680°C. Based on the results from the RHEED observations and X-ray diffraction analysis, we found that c-GaN with the growth direction of < 110 > was preferentially grown on the (001) rutile TiO_2 substrates. The formation of c-GaN was also confirmed by cathodoluminescence, in which luminescence peak was observed at 3.24eV.

L3.28
CHARACTERIZATION OF CUBIC GaN FILMS USING AlN/GaN ORDERED ALLOY ON THE GaAs(100) BY RF-MBE. Junichi Shike, Atsushi Shigemori, Ryuhei Kimura, Koichi Ishida, Kiyoshi Takahashi, High-Tech Research Center, Faculty of Science and Engineering Teikyo University of Science and Technology, Uenohara, Kitatsuru-gun, Yamanashi, JAPAN.

Metastable cubic GaN (c-GaN) is expected to have many advantages in physical properties over those of the hexagonal phase. We reported that using an AlGaN layer formed by nitridation of an $Al_{0.17}Ga_{0.83}As$ buffer was an efficient process for ensuring highly pure c-GaN growth. [1][2] But there still remain some problems regarded AlGaAs growth. The first relates to fluctuation of Al molar content, which in turn affects significantly the purity of the structural phase of the epilayer. The second is the difficulty of maintaining high quality stoichiometric growth for extends time because strict control of each beam flux (Al, Ga and As) is required. In this work, $(AlN)_m/(GaN)_n$ ordered alloy (OA) is employed instead of AlGaAs buffer layer. It is expected that uniform effective Al molar content can be achieved by varying the ratio of each layer thickness. This process makes it is easy to maintain high quality stoichiometric growth for extended periods because all constituent layers are binary materials. By using an OA layer, the effective Al molar content can keep low enough to prevent both the generation of hexagonal nuclei. Cubic GaN films were grown on GaAs substrates by RF-MBE. After thermal annealing, a GaAs buffer layer was grown. Following growth of the GaAs buffer layer, nitridation was carried out for 10 seconds. Subsequent to nitridation, alternative supplies of Al and Ga flux were provided using a shutter system controlled by personal computer to form an AlN/GaN OA layer. We obtained high quality c-GaN films successfully grown on $(AlN)_1/(GaN)_4$ OA (5 periods). Dominant c-GaN epilayer growth was confirmed by insitu-RHEED observation and it reflection observed by XRD with ω-2θ, but small amount of mixing of hexagonal phase on (111)B facets was speculated by X ray Pole figure and low temperature Photoluminescence. References [1] R. Kimura, K. Takahashi and H.T. Grahn, Proc. of MRS Fall Meeting Vol 639 (2001), G3.46.1. [2] R. Kimura and K. Takahashi, Proc. of Int. Conf. on MBE-XI, Beijing (2000), 456.

L3.29
CONTROL OF THE 2D-3D TRANSITION FOR THE GROWTH OF CUBIC GaN/AlN NANOSTRUCTURES. Esteban Martinez-Guerrero, Christoph Adelmann, Bruno Daudin, Jean-Luc Rouviere, Henri Mariette, CEA/CNRS group Nanophysique et Semiconducteurs, CEA Grenoble, FRANCE.

The Stransky-Krastanow (SK) growth mode of strained layers which gives rise to a 2D-3D morphology transition is studied in details for the cubic GaN/AlN system. Besides the lattice parameter mismatch which governs this transition, we evidence the importance of two other parameters, namely the substrate temperature and the III/V flux ratio. Cubic GaN and AlN were grown by plasma assisted MBE. The substrate consist of a thick (001) SiC layer grown on (001) Si. The GaN MBE growth was monitored in-situ using reflection high energy electron diffraction (RHEED) which allows us to follow both the evolution of the surface morphology and the strain state of the GaN layer by analysing the streak spacing in the RHEED pattern. The dimensionality of the grown GaN (2D wells or 3D dots) is also assessed by structural studies (AFM and TEM) and optical measurements. For a growth temperature Ts as low as 600°C, the strain relaxation occurs without any change of the surface morphology. This behavior corresponds to a plastic relaxation with the formation of dislocation into the 2D layer. By contrast, for Ts higher than 700°C, the formation of GaN quantum dots is obtained after a critical thickness of about two monolayers (MLs). This can be explained by a kinetic effect: the adatoms are more mobile at higher growth temperature, allowing the formation of GaN dots. The second parameter which is crucial to control the fabrication of these nanostructures, is the III/V flux ratio. Under stoechiometric conditions, the 2D-3D transition occurs after the growth of 2MLs. By increasing the Ga flux as compared to the nitrogen one, the SK transition is drastically delayed, alloying the growth of coherent GaN/AlN quantum wells. This behavior can be account by considering the increase of surface energy when growing with a Ga excess onto the surface.

L3.30
COMPRESSIVE AND TENSILE INTRINSIC STRESS EVOLUTION IN ALUMINUM NITRIDE FILMS. A. Rajamani, S. Hong, R. Beresford, A. Bhandari, E. Chason, B.W. Sheldon, Brown University, Division of Engineering, Providence, RI.

Epitaxial aluminum nitride films deposited by molecular beam epitaxy grow by the Volmer-Weber (island) mode. They show evolution of tensile intrinsic stress at roughly the point where islands coalesce. After the tensile maximum is reached, a compressive source predominates. We believe that this compressive stress is driven by the excess chemical potential of adatoms due to the growth flux. To test this hypothesis, a number of experiments were conducted to vary the intrinsic stress. A finite element model that couples both the compressive and tensile stress mechanisms was developed. These calculated results were compared directly with the experimental data to develop a more accurate description of the mechanisms which control stress evolution during film growth.

L3.31
ALUMINUM NITRIDE GROWTH BY HALIDE VAPOR TRANSPORT EPITAXY. Vladimir Tassev, David Bliss, John Bailey, David Weyburne, Air Force Research Laboratory, Hanscom AFB, MA.

Single crystal aluminum nitride wafers are potentially well-suited substrates for GaN-based devices because of their high thermal conductivity, close lattice match to other III-nitride alloys, and short wavelength UV transparency. However, bulk growth of AlN is not advanced enough for large-scale wafer processing. As an alternative, we have developed an epitaxial process for growth of thick-layer AlN on sapphire, designed to be thick enough for thermal dissipation and yet with high UV transparency. High quality AlN layers with thickness up to 50 μm have been grown by HVTE on sapphire substrate covered in advance with about 1 μm thick MOCVD gallium or aluminum nitride film. The deposition temperature and the total reactor pressure were in the range of 900-1100°C and 0.01 1 atmosphere, respectively. The growth process relayed to $AlCl_3$ $n.NH_3$ type of adducts as a source of aluminum, anhydrous ammonia is used as a nitrogen source, with a carrier gas of nitrogen or hydrogen. The total flow rate was less than 350 sccm and the maximum growth rate under these conditions was 60 μm/h, which makes the proposed process highly efficient. Additionally, this new technique eliminates the main difficulties of the conventional HVPE growth, where aluminum oxidation and the strong reactivity of aluminum chloride with quartz create the potential for oxygen contamination. This study shows the effect of temperature, gas flow velocities, and reactor pressure on the growth rate and layer quality. It is found that the growth rate and the layer thickness strongly depend on proper adduct preparation. Two types of surface morphology rough and smooth texture were observed under different growth conditions. They were related to two different growth mechanisms the rough from

precipitation of particles formed in the gas stream and smooth surfaces resulting from highly oriented epitaxial growth.

L3.32
AlN BULK CRYSTAL GROWTH BY SUBLIMATION SANDWICH METHOD. E.N. Mokhov, A.D. Roenkov, Yu.A. Vodakov, Crystal Growth Science and Technology Lab, St. Petersburg, RUSSIA; Yu.N. Makarov, Semiconductor Technology Research Inc, Richmond, VA; H. Helava, The Fox Group Inc, Livermore, CA.

Aluminum nitride is a promising substrate material for high-power electronics and ultra-violet optoelectronics. In the present paper, we report on the AlN bulk crystal growth by sublimation sandwich method. 4H- and 6H-SiC wafers both of (0001)C and (0001)Si orientations were used as substrates. Growth was carried out at temperatures of 1900-2250^{0}C at atmospheric pressure in a nitrogen environment. High purity AlN powder was employed as the source of Al and N_2 species. Growth duration was varied from 3 up to 30 hours. In our experiments we have varied the distance between the source and the substrate from 2 up to 10 mm. As a result of process optimization, AlN crystals of 12 mm in diameter and up to 5 mm long have been grown with the rate close to 0.5 mm/h. The crystals were transparent and slightly amber-colored. Characterization of the crystals grown on different substrates has revealed that the AlN crystals of the better quality could be obtained on on-axis SiC (0001)Si wafers. Cracks generating mainly at the crystal/substrate interface were the main type of defect formed during the furnace cooling. Our experiments demonstrate that an increase in growth duration results in dramatic reduction of the crack density. Special analysis has been performed to study the impact of substrate quality. We have found that many substrate defects were inherited in an AlN crystal. The specific features of the nitrogen kinetics on AlN surface and the mechanisms of species mass transport are discussed.

L3.33
EXPERIMENTAL AND THEORETICAL ANALYSIS OF HEAT AND MASS TRANSPORT IN THE SYSTEM FOR AlN BULK CRYSTAL GROWTH. M.V. Bogdanov, S.Yu. Karpov, A.V. Kulik, M.S. Ramm, Yu.N. Makarov, Semiconductor Technology Research Inc, Richmond, VA; R. Schlesser, Z. Sitar, NC State Univ, Mat. Sci. Eng. Dept, Raleigh, NC.

Growth of bulk AlN crystals is studied both experimentally and numerically. The heat transfer in the whole growth system used at NCSU is modeled. A special attention is given to the mechanisms of heat transfer in the AlN powder source, which consists of the conduction and radiation parts. By calculating radiative heat transfer in the AlN powder it is important to take into account also heat radiation through the granules. It is found that the effective heat conductivity of the AlN powder is lower than that of the crystalline AlN and that it depends on the powder porosity and nitrogen pressure. Species transport in the growth chamber is simulated using a simple 1D model of the process. The model validation is performed using the experimental data obtained at NCSU. The effects of the temperature gradient between the source and seed, and crucible tightness on AlN crystal growth are studied experimentally and theoretically. The most of experiments are performed at external pressure of 400 Torr. We have found that in the temperature range of 2100-2200^{0}C higher AlN growth rates can be obtained with use of high temperature gradients between the source and seed, and in a tightly closed crucible.

L3.34
THE INFLUENCE OF SUBSTRATE SURFACE POLARITY ON OPTICAL PROPERTIES OF GaN GROWN ON SINGLE CRYSTAL BULK AlN. G. Tamulaitis, I. Yilmaz, M.S. Shur, Rensselaer Polytechnic Institute, Dept of ECE and CIE, Troy, NY; R. Gaska, Sensor Electronic Technology, Inc., Latham, NY; C. Chen, J. Yang, E. Kuokstis, A. Khan, Univ of South Carolina, Dept of EE, Columbia, SC; C. Rojo, L. Schowalter, Crystal IS, Inc., Latham, NY.

We will report on comparative study of GaN layers grown using low-pressure MOCVD over Al-face and N-face bulk AlN substrates. Single crystal bulk AlN substrates were grown using a self-seeded sublimationrecondensation technique. GaN epitaxial layers were grown over approximately 6 degrees off c-axis substrates. The deposition of approximately 0.5-1 μm thick GaN layers on both Al-face and N-face substrates was performed in a single MOCVD growth run. We measured CW and pulsed photoluminescence (PL) in the temperature range from 8 K to 300 K. He-Cd laser (wavelength 325 nm) and 4-th harmonic of YAG: Nd laser (wavelength 266 nm, pulse width 5 ns) were used for CW and pulsed excitation, respectively. Room temperature CW PL peak positions for Al-face and N-face AlN substrate polarities were 3.40 eV and 3.39 eV, respectively, which are significantly lower than for our typical GaN on sapphire (3.416 eV 3.422 eV) and on 6H-SiC (3.41 eV). Also, GaN layers on N-face AlN had much stronger yellow emission. PL line width in GaN on N-face AlN exhibited nearly linear dependence on temperature. In contrast, the line narrowed in GaN on Al-face substrates approximately 3-4 times by reducing temperature from 300 K to 150 K and remained practically unchanged at lower temperatures. At high pulse excitation intensities, lower threshold for stimulated emission was measured in GaN layers on N-face AlN, whereas strong heating of the electron-hole plasma was observed in the layers grown on Al-faced substrates. We attribute the observed PL behavior to different defect structure and exciton localization in GaN layers over AlN substrates with different surface polarity.

L3.35
LOW PRESSURE GROWTH OF BULK GaN FROM GALLIUM/ INDIUM ALLOYS. Challa Bekele, Kathleen Kash, John C. Angus, Cliff C. Hayman, Case Western Reserve Univ, Cleveland, OH.

Activated nitrogen from a DC plasma was reacted with liquid gallium/indium alloys heated at temperatures near 700C. Diluting the gallium with an inert element increases the GaN solubility and can lead to more stable growth and higher growth rates. Thermodynamic calculations [1] and experiments [2] suggested that InN is not stable at 700 C at nitrogen activities achieved in the reactor; and thus In metal could be used as inert element to dilute the gallium. GaN was grown from alloys of gallium in indium with varied atomic percent. GaN bulk growth from the alloys in activated nitrogen plasma on a MOCVD grown GaN seed layer was also investigated. Characterization was accomplished using EDAX, X-ray diffraction and photoluminescence spectroscopy. [1] Brian Douglas Schultz, M.Sc Thesis, Department of Chemical Engineering, CWRU [2] Michael Timothy Grossner, M.Sc Thesis, Department of Chemical Engineering, CWRU

L3.36
OPTICAL CHARACTERIZATION OF BULK GaN GROWN FROM A Na FLUX. B.J. Skromme, K. Palle, Dept of Electrical Engineering and Center for Solid State Electronics Research, Arizona State University, Tempe, AZ; C.D. Poweleit, Dept of Physics and Astronomy, Arizona State University, Tempe, AZ; H. Yamane, M. Aoki, Institute for Advanced Materials Processing, Tohoku University, JAPAN; F.J. DiSalvo, Dept of Chemistry and Chemical Biology, Cornell University, Ithaca, NY.

Bulk GaN crystals (platelets and prisms) up to several mm in size, grown by a Na/Ga flux method have been characterized using room and low temperature photoluminescence, Raman scattering, cathodoluminescence (CL) imaging, and reflectance. High crystal quality and purity are evident in the narrow (down to 0.22 meV FWHM) excitonic luminescence linewidths achieved, and Raman scattering implies free electron concentrations in the mid 10^{16} to low 10^{17} cm^{-3} range. Pronounced correlations of growth conditions and spectroscopic properties are found. Crystal polarity affects the incorporation of residual Zn acceptors and deep level luminescence bands. Striations are found in some of the smaller platelets by CL imaging, but are absent in the prismatic crystals.

L3.37
THE IMPACT OF GROWTH CONDITIONS ON THE BACKGROUND IMPURITY CONCENTRATION OF GALLIUM NITRIDE WAFERS. Robert P. Vaudo, Xueping Xu, Edward L. Hutchins, Allan D. Salant, George R. Brandes, ATMI, Inc., Danbury, CT.

A promising pathway for improving the reliability of GaN-based electronic devices is to form the devices on low defect density GaN substrates produced by hydride vapor phase epitaxy (HVPE). In addition to low defect density, the HVPE approach is inherently scalable to very large wafer area. While the background electron concentration in HVPE GaN material has been reduced by several orders of magnitude since the 1970s, the purity of the material must be further increased and/or a deep level compensating impurity must be incorporated to make the material suitable for high frequency electronic applications. In this work, we grew unintentionally doped GaN under a variety of growth conditions and studied how the background impurity concentration changed with process conditions. The concentration of background impurities was determined using secondary ion mass spectroscopy (SIMS) and in cases where additional sensitivity was required, glow discharge mass spectroscopy (GDMS). Resistivity and Hall effect measurements were used to assess carrier type, concentration and mobility. The principal impurities were silicon and oxygen, and the impurity concentration varied considerably with growth conditions and growth time (along the growth axis). In the highest purity material, silicon was the only impurity detected and the background electron concentration was 1×10^{16} cm^{-3} with a corresponding Hall mobility of 1000 cm^2 V^{-1} s^{-1}. Impurity concentrations of both oxygen and silicon were sensitive to growth temperature. Oxygen concentration increased with decreasing growth temperature and exceeded 10^{17} cm^{-3} for temperatures less than 1000°C. In contrast, the silicon concentration was found to

increase with temperature. The silicon and oxygen concentration decreased with growth time and GaN thickness. A full analysis of the impact of growth conditions on the impurity concentration and distribution, along with the resulting electrical properties of the HVPE GaN substrates produced, will be presented.

L3.38
LOW-ELECTRON-ENERGY CATHODOLUMINESCENCE STUDY OF POLISHING AND ETCHING EFFECTS ON THE OPTICAL PROPERTIES OF BULK SINGLE-CRYSTAL GALLIUM NITRIDE. Lawrence H. Robins, National Institute of Standards and Technology, Gaithersburg, MD; Bruce Steiner, National Institute of Standards and Technology, Gaithersburg, MD (retired); Norman A. Sanford, National Institute of Standards and Technology, Boulder, CO; Carmen Menoni, Colorado State University, Fort Collins, CO.

Surface preparation techniques such as mechanical polishing and ion-beam etching are often used to optimize the morphology and microstructure of the substrate surface prior to epitaxial film growth. There is a need for characterization methods that are sensitive to polishing and etching effects on the near-surface structural, optical and electronic properties. We used low-electron-energy cathodoluminescence (CL) spectroscopy to examine the near-surface optical properties of high-pressure high-temperature grown single-crystal GaN platelets. The surfaces were prepared either by mechanical polishing alone, or by mechanical polishing and subsequent chemically assisted ion-beam etching (CAIBE) to a depth of ~200 nm. The electron penetration depth beneath the GaN surface (for CL) was controlled by varying the accelerating voltage. CL spectra were acquired at low temperature (T=15 K) at voltages of 2.8 kV, 5.4 kV, and 10.6 kV, corresponding to calculated maximum (or average) penetration depths of 78 nm (27 nm), 235 nm (80 nm), and 720 nm (245 nm) respectively. The near-band-edge CL spectra show a comparatively narrow peak at ~3.47 eV, ascribed to donor-bound-exciton recombination, and a broader peak at ~3.3 eV, ascribed to deep defect or donor-acceptor pair recombination. On the mechanically polished surface, the donor-bound-exciton peak broadens and decreases in intensity relative to the lower-energy peak as the penetration depth decreases, indicating the presence of a near-surface damage layer. As assessed by the variation of the CL lineshape with penetration depth, the ion-beam etching removes some but not all of the polishing damage. From the CL results, the total thickness of the polishing-induced damage layer is $\geq$400 nm.

L3.39
PRODUCTION OF SAPPHIRE BLANKS AND SUBSTRATES FOR BLUE LEDS AND LDs. Chandra P. Khattak, Frederick Schmid, Paul J. Guggenheim, Maynard B. Smith, Henry H. Rogers, and Kurt Schmid, Crystal Systems Inc., Salem, MA.

Sapphire blanks and substrates offer the lowest cost and high performance for blue light emitting diodes (LEDs) and laser diodes (LDs). The potential of this market growth is dependent on producing high quality substrates at low cost. Production of sapphire boules using the Heat Exchanger Method (HEM) has been extended to 34-cm diameter boules so that large area substrates can be produced economically. Orientation of boules and characterization can affect the quality of substrates. Boules have been grown to 38-cm diameter, and efforts are being pursued to produce 50-cm diameter sapphire boules. Procedures have been developed to correlate sapphire production with specifications of the substrates to achieve high quality at low cost. A new multiwire slicing technology, the Fixed Abrasive Slicing Technology (FAST), is in manufacturing mode producing sapphire blanks with minimal kerf loss and high material utilization. FAST utilizes diamond-plated wires held in a frame and reciprocated to slice a rotating sapphire workpiece. This technology has been used for effective slicing of 2-inch and 3-inch diameter sapphire to produce high-quality blanks. Comparisons of FAST with alternative slicing technologies will be discussed. Processing of sapphire blanks to produce substrates has also been carried out. Details of sapphire crystal growth, slicing and finishing of blanks will be discussed to meet current needs as well as expanding the production to 6-inch diameter sapphire blanks and substrates using existing technologies to meet future needs.

L3.40
TRANSPORT AND CHEMICAL MECHANISMS IN GaN HALIDE VAPOR PHASE EPITAXY. S.Yu. Karpov, A.S. Segal, D.V. Zimina, S.M. Smirnov, A.P. Sid'ko, Soft-Impact Ltd, St. Petersburg, RUSSIA; Yu.N. Makarov, STR Inc, Richmond, VA; D. Martin, V. Wagner, M. Ilegems, Institute for Quantum Electronics and Photonics, Swiss Federal Institute of Technology, Lausanne, SWITZERLAND.

Halide Vapor Phase Epitaxy (HVPE) is a promising technique for growing thick GaN epilayers and quasi-bulk crystals with reduced dislocation density. To be widely employed in industry, HVPE should provide high growth rate and good uniformity on large-diameter wafers and reduced parasitic deposition on reactor walls for avoiding particle generation. In this work, we show by detailed three-dimensional modeling that flow dynamics in HVPE is the factor extremely important for the growth rate uniformity. The growth rate distribution across the wafer is found to depend on the reactor geometry, particular precursor flow rates, substrate rotation, etc. To identify the growth mechanism, we have carried out a parametric experimental and modeling study of HVPE in a horizontal tube reactor. The theoretical predictions are found to agree reasonably with original and published experimental data. In the paper, we discuss the role of surface kinetics and thermodynamics in HVPE of GaN.

L3.41
LATTICE CONSTANTS VARIATION IN THE GaN:Si SINGLE LAYERS GROWN BY HVPE. A.S. Usikov, G. Gainer, O.V. Kovalenkov, M. Mastro, A.I. Pechnikov, D.V. Tsvetkov, V.A. Soukhoveev, Y.V. Shapovalova, Technologies and Devices International, Silver Spring, MD.

Due to its high growth rate and high material quality, hydride vapor phase epitaxy (HVPE) is an excellent method for fabricating quasi-bulk GaN material or single layer GaN templates to be used as substrates for subsequent growth of device structures. We will discuss the variation of structural properties of GaN templates with Si-doping, which is significant because structural defects can penetrate from the template to the upper growth structure. The templates were grown by HVPE on (0001) sapphire substrates. All samples were crack-free with GaN thickness and doping varying from 2.5 to 13 μm and 5×10^{17} to 3×10^{18} cm^{-3}, respectively. Lattice constant measurements were performed by double crystal x-ray diffraction using the Bond method with an accuracy of ±0.0001 Å. Lattice constant c was measured using refl. (00.6), and constant a was evaluated using asymmetric refl. (20.5). Previous investigations of thick HVPE GaN layers have shown that a strong strain gradient exists along the part of layer near the substrate, and the rest of the layer has practically uniform stress up to the top of the layer (Appl. Phys. Lett. **80**, 1550 (2002)). We observed no noticeable relation between lattice constants and total layer thickness. Apparently, Si has a strong influence on stress relaxation only in the thin region near the substrate interface. However, we found that the *c* and *a* lattice constants have non-monotonic behavior with Si-doping. There was a kink in the lattice constant dependence on Si concentration. GaN template photoluminescence properties will also be discussed. The proper choice of Si-doping concentration and growth conditions is useful for strain engineering and defect minimization in GaN:Si templates important for device applications.

L3.42
TEMPERATURE AND EXCITATION POWER DEPENDENCE OF THE LUMINESCENCE DECAY IN FREE-STANDING HVPE GaN. Qing Yang, Henning Feick, and Eicke R. Weber, Department of Materials Science and Engineering, University of California, Berkeley, CA.

Today, very high quality GaN materials grown by hydride vapor-phase epitaxy (HVPE) are available. The progress in this field is driven by the potential application of large-area HVPE GaN wafers as substrates for GaN homoepitaxy. Thick HVPE layers are characterized, for example, by very narrow luminescence lines. This enables the study of carrier dynamics with unprecedented selectivity to the various decay channels. Here we report on the luminescence decay of different donor species, and we attempt to systematically assess the influence of nonradiative defect centers on the carrier dynamics using controlled particle radiation exposures. Picosecond time-resolved photoluminescence was studied in the temperature range from 5 to 410 K on two thick (160 μm and 250 μm) free-standing HVPE GaN layers. The room-temperature luminescence decay time constants are found to be on the order of a few nanoseconds. Luminescence spectra at low temperature display clearly resolved lines of free-excitons, bound-excitons, bound-exciton two-electron transitions, and longitudinal optical (LO) phonon-assisted transitions. Exciton and carrier recombination dynamics are analyzed as a function of temperature and excitation density. From the analysis of the two-electron transitions, we are able to determine the exciton capture and luminescence decay rates independently for both dominant shallow donors, Si and O. In addition, differences in the luminescence decay dynamics of the Ga and N-polar surface are studied. Exposure to 2.7×10^{14} cm^{-2} 55 MeV protons reduced the luminescence decay time considerably, and the effect of the added nonradiative defect centers on the temperature dependence of the lifetime and of the integrated luminescence are discussed.

L3.43
OPTICAL PROPERTIES OF GaN THICK FILMS GROWN BY NOVEL HYDRIDE VAPOR PHASE EPITAXY. Minseo Park, J.J. Cuomo, Department of Materials Science and Engineering, North Carolina State University, Raleigh, NC; Y.C. Chang, A.L. Cai, J.F.

Muth, R.M. Kolbas, Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC; R.J. Nemanich, Department of Physics, North Carolina State University, Raleigh, NC; A. Hanser, J. Bumgarner, Kyma Technologies, Inc., Raleigh, NC.

The thick films of novel HVPE-grown GaN were studied using X-ray diffraction, micro-Raman spectroscopy, (time-resolved) photoluminescence spectroscopy, and cathodoluminescence spectroscopy. The sample was grown with a newly developed HVPE technique which allows growth of high quality GaN on a large substrate area of 4 in. The FWHM of the X-ray rocking curve for our sample is 375 arc-sec. Only the allowed modes were observed in the polarized Raman spectra. The GaN films were relatively stress-free. Free carrier concentration was determined by both van der Pauw Hall measurement and Raman measurement. The FWHM of the near-band edge PL peak was 56.4 meV at room temperature and 22.3 meV at 77K, respectively. No peak due to deep level transition was observed. The cathodoluminescence spectrum also reveals sharp band-edge transition. Time-resolved PL shows clear indication of a bi-exponential decay of the luminescence peak. The film was thermally stable upon annealing in N2 ambient, which was investigated by Raman scattering, photoluminescence, and time-resolved photoluminescence spectroscopy. It was concluded that the HVPE-grown GaN films are of high crystal quality. The optical and structural characteristics of free-standing bulk GaN will be also presented.

L3.44
ANALYSIS OF < 0001 > TILT GRAIN BOUNDARIES IN GaN AT THE ATOMIC SCALE. Jun Chen, Inst Univ de Technologie, Lab Univ de Recherche Scientifique d'Alencon, Damigny, FRANCE; Gerard Nouet, Pierre Ruterana, ISMRA CRISMAT ESCTM, Caen FRANCE.

Epitaxial layers of GaN contain a very high density of threading dislocations. In the first stage of growth they may form low and high angle grain boundaries. Energetic caculations of < 0001 > tilt grain boundaries have been performed in the range 0-60° in order to determine the special structural units corresponding to the misorientation of low energy. From two special units it is possible to describe the other misorientations in terms of dislocation cores exhibiting the three types previously analysed by high resolution transmission electron microscopy: 8,5/7 and 4 atom cores.

L3.45
COMPARISON OF DISLOCATION DENSITY MEASUREMENT TECHNIQUES FOR GaN. Y.S. Choi, B.T. Lee, Photonic and Electronic Thin Film Laboratory, Department of Materials Science and Engineering, Chonnam National University, Gwang-ju, KOREA.

Threading dislocations are the most important defect in developing high brightness GaN-based LED devices. Many techniques have been so far reported to measure the density of dislocations. While transmission electron microscopy has been known to give the most accurate values, this technique is destructive and requires tedious sample preparation process. EPD is a commonly used technique for defect investigation. and other techniques such as DCXRD and CL are recently used for investigating optical characterization. In this study, dislocation density in about 25 GaN layers grown by metal-organic chemical vapor deposition (MOCVD) was measures using various techniques such as transmission electron microscopy (TEM), Cathodoluminescence (CL), double crystal X-ray deffraction, and observation of surfaces using atomic force microscopy(AFM) and field-emission scanning electron microscopy (FE-SEM) after etching with molten KOH and H3PO4, and the results were compared. The results indicated that the significantly lower dislocation density are measured by CL and EPD when compared with results of the plan-view TEM observation. As an example, measurement of a same sample resulted in $7.6*10^9 cm^{-2}$ by plan view TEM, $1.6*10^7 cm^{-2}$ by CL, $1*10^6 cm^{-2}$ by the EPD(etch-pit density) observation using molten KOH, and $2*10^5 cm^{-2}$ using H3PO4. Further details will be discussed during the presentation.

L3.46
MICROCATHODOLUMINESCENCE AND ELECTRON BEAM INDUCED CURRENT OBSERVATION OF DISLOCATIONS IN FREESTANDING THICK n-GaN SAMPLE GROWN BY HYDRIDE VAPOR PHASE EPITAXY. A.Y. Polyakov, A.V. Govorkov, N.B. Smirnov, Institute of Rare Metals, Moscow, RUSSIA; Z-Q. Fang, D.C. Look, Wright State Univ, Semiconductor Research Center, Dayton, OH; S.S. Park, J.H. Han, Samsung Advanced Institute of Technology, Suwon, KOREA.

Capacitance-voltage C-V profiling, deep levels spectra DLTS measurements with electrical and optical injection, microcathodolumunescence MCL spectra measurements, MCL and electron beam induced current EBIC imaging of the free standing n-GaN samples grown by hydride vapor phase epitaxy were made. Dark spot defects in plan-view EBIC and MCL images and dark line defects in MCL images taken on the cleaved surface of the samples could be associated with dislocations. MCL spectra measurements in the vicinity of dislocations and in the matrix do not reveal specific luminescence bands that could be attributed to dislocations but rather suggest that dislocation regions have higher density of deep non-radiative traps. C-V and DLTS results bear evidence of the presence of a thin damaged layer at the surface of the samples caused by reactive ion etching. This has a much lower concentration of free electrons and much higher density of deep traps than the bulk of the film.

L3.47
TEM ANALYSIS OF STRESS RELIEF MECHANISM ASSOCIATED WITH THREADING DISLOCATIONS IN GaN/AlGaN/GaN. N. Kuwano, Kyushu Univ, KASTEC, Kasuga, JAPAN; T. Tsuruda, Kyushu Univ, Dept of Adv Sci for Electronic & Mater, Kasuga, JAPAN; S. Terao, S. Kamiyama, H. Amano and I. Akasaki, Meijo Univ, Dept of M.S.E., Nagoya, JAPAN.

AlGaN alloy semiconductor is a key material for light emitting diodes (LEDs) in short wavelength range. However, fabrication of heterostructures containing AlGaN layers is very difficult since an AlGaN layer grown on GaN usually has cracks on the surface. Some of the present authors succeeded in growing a crack-free AlGaN layer on GaN by inserting a thin AlN interlayer (*IL*-AlN) deposited at a low temperature. [1,2] We found that a number of a-type threading dislocations (TDs) are generated at the *IL*-AlN and they are annihilated quickly above the interface of GaN/AlGaN. [3] The dislocations play an important role in stress relief in the top layer of GaN. In the present study, transmission electron microscope (TEM) observation was performed to clarify the behavior of the dislocations. The heterostructure of GaN / $Al_{0.28}Ga_{0.72}N$/*LT*-AlN/GaN/*IL*-GaN / α -Al_2O_3(0001) was made by the metalorganic vapor phase epitaxy. TEM specimens were prepared with an argon ion mill and a focused ion beam (FIB) apparatus. It was confirmed from the cross section TEM observation that the a -type TDs are generated and annihilated in pairs. The annihilation in pairs reflects disappearance of excess lattice planes in GaN on AlGaN. The behavior of TDs relieves the compressive stress and decreases the number of TDs in the GaN layer. High resolution images were taken to clarify the formation process and the morphology of paired TDs that were analyzed with the simple theory of dislocations.
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L3.48
SCREW DISLOCATIONS IN MBE GaN LAYERS GROWN ON TOP OF HVPE LAYERS; ARE THEY DIFFERENT? Z. Liliental-Weber, J. Jasinski, D. Zakharov, and J. Washburn, Materials Science Division, Lawrence Berkeley National Laboratory, Berkeley CA; M. O'Keefe, National Center for Electron Microscopy, Berkeley, CA; H. Morkoc, Virginia Commonwealth University, Richmond, VA.

It was shown earlier that screw dislocations in Ga-rich MBE layers grown on an HVPE substrate cause leakage current and it was suggested that their cores might be Ga rich. In the present work Transmission Electron Microscopy was applied to study the HVPE template and the MBE overlayers in plan-view and cross-sections. It was observed that screw dislocations in the HVPE layers are decorated by small voids arranged along the dislocation. However, voids were not formed along screw dislocations in the MBE overlayers grown with excess Ga despite the fact that Ga droplets were observed on the layer surface as well as imbedded in the layer. The fact that these voids are formed along screw dislocations but not along edge dislocations suggests that formation of the voids is related to the core structure of the dislocation. For screw dislocations the strain field along [0001] is symmetrical but for edge dislocations, compressive and tensile stress on opposite sides of the dislocation, may make void formation less likely. By applying a direct reconstruction of the phase and amplitude of the scattered electron wave from a focal series of high resolution images, the core structures of screw dislocations in both materials have been studied in order to see if the core structure in HVPE template layer and the MBE overlayer is different. This will be discussed in detail during the presentation.

L3.49
PIEZORESPONSE FORCE MICROSCOPY OF INVERSION DOMAINS IN AlN/Si. B.J. Rodriguez, A. Gruverman, A.I. Kingon, R.J. Nemanich, North Carolina State University, Department of Physics and Department of Materials Science and Engineering, Raleigh, NC.

The measurement of the piezoelectric properties of III-nitrides with high spatial resolution is of importance for the design and performance

of GaN based electronic and optoelectronic devices. Aditionally, nanoscale level investigation of the piezoelectric behavior of nitride thin films, bulk crystals and heterostructures is of considerable interest for determining how interfaces, defects and inversion domain boundaries affect device performance. When an electric field is applied to a piezoelectric material, it strains due to the converse piezoelectric effect. Several techniques can be used to measure these small piezoelectric displacements. The piezoresponse force microscopy (PFM) technique is useful because the tip can be rastered to generate images of the phase and of the magnitude of the piezoelectric response in addition to being able to measure the piezoelectric displacement at single points on a sample. Another advantage of this technique is that it can resolve nanometer variation in the piezoelectric properties of a sample. Piezoelectric constants of epitaxial AlN and GaN/AlN layers as well as the polarity distribution of GaN based lateral polarity heterostructures have previously been investigated by PFM. In this study, simultaneous imaging of surface morphology as well as the phase and magnitude of the piezoelectric response is performed by PFM on an AlN/Si film with known mixed polarity. We demonstrate that the polarity distribution can be deduced from the phase image of the piezoresponse with nanometer scale spatial resolution. We present images of AlN/Si samples with regions of opposite piezoresponse phase, which indicate the presence antiphase or inversion domains. We discuss the possibility of employing this technique for determination of the orientation of bulk crystals.

L3.50
PHOTOREFLECTANCE SPECTROSCOPY OF Al/GaN/GaN HEMT STRUCTURES. D.K. Gaskill, O.J. Glembocki, B. Peres[a], and R. Henry, Naval Research Laboratory, Washington DC; [a]EMCORE, Somerset, NJ.

The photoreflectance (PR) spectroscopy of AlGaN/GaN HEMT structures is discussed. We show that PR can provide valuable information not only about the band structure of the HEMTs, but also about the presence of interfacial traps. The spectral features below the band gap are shown to be due to index of refraction modulation (first derivative), possibly due to electric field modulation of the dielectric function. The spectral feature near the bandgap is compared to spectra obtained from constant doped, single epilayer samples and has many similarities except the band gap is shifted to higher energies. The cause of this shift may be due to strain near the GaN/AlGaN interface or from band filling of the 2DEG levels. The pump intensity dependence of the PR signal is due to an open circuit photovoltage mechanism, which has components in-phase and out-of-phase with the modulation. Previously, we have used photoreflectance optical impedance spectroscopy to show that the phase lag obtained is related to the presence of barriers and/or traps in the epitaxial structure which then effect the temporal response of the photovoltage. For the case of nitride- HEMT structures we interpret the phase lag in a similar fashion and suggest that it should be further investigated because of its potential in non-destructively evaluating the performance of nitride-device structures.

L3.51
COMPOSITIONAL FLUCTUATIONS IN $Al_xGa_{1-x}N$ BUFFER LAYERS GROWN ON 6H-SiC BY MOVPE. R. Kröger, P. Ryder, S. Einfeldt, Inst of Solid State Physics, University of Bremen, Bremen, GERMANY; R.F. Davis, Dept of Materials Science and Engineering, North Carolina State University, Raleigh, NC.

$Al_xGa_{1-x}N$ is often used as a buffer layer on 6H-SiC (0001) substrates for the subsequent growth of GaN because its dopability allows the fabrication of vertical device structures. To study the effect of the buffer layer on the GaN films, high temperature GaN layers with varying thickness (10 to 1000 nm) were grown on top of $Al_xGa_{1-x}N$ (with x = 0.15) by metal organic vapor phase epitaxy. The microstructure and chemical composition of the layers were characterized using atomic force microscopy (AFM) and transmission eletron microscopy (TEM) in combination with energy dispersive X-ray spectroscopy (EDS). Narrow trenches were found on the surface of both the buffer layers and thin GaN films grown thereon. The trenches have no preferred crystallographic orientation and their density decreases with increasing GaN film thickness. Beyond a GaN layer thickness of about 500 nm, no trenches were observed. Cross sectional TEM analysis revealed that the trenches were v-shaped and of variable depth. Both Elemental distribution mapping and a quantitative determination of the Al concentration by EDS indicate a strong lateral and vertical variation of the Al content in the buffer layer. Elliptical areas with an Al mole fraction larger than 0.12 and a lateral size between 250 and 500 nm were found both at the $SiC/Al_xGa_{1-x}N$ and the $Al_xGa_{1-x}N$ /GaN interfaces. They have a thickness of about 30 nm and are embedded in $Al_xGa_{1-x}N$ with an Al mole fraction of only a few percent. Furthermore, the Al rich regions at the two interfaces alternate in lateral direction. The spatial order of the compositional fluctuations and the formation of the trenches is discussed based on a model, which takes into account both the island growth mode of $Al_xGa_{1-x}N$ on SiC and the strain-driven incorporation of Al during growth.

L3.52
HIGH SPATIAL RESOLUTION CATHODOLUMINESCENCE MEASUREMENT OF InGaN. Hisashi Kanie, Hiroaki Okado, Kenya Yoshimura, Dept of Applied Electronics, Tokyo Univ of Science, Chiba, JAPAN.

Although the InGaN active layer plays an important role in a high efficiency light emitting diode ranging from violet to green wavelength regions, the emission mechanize is not yet clear, which is partly because of the existence of the stress within the layers. We synthsized InGaN microcrystals with a diameter of 0.1 to 10 μm by nitridation of In or Ga sulfide with ammonia at 850 and 950°C. Measuring room temperature cathodoluminescence of InGaN grown at 850°C by an electron probe microanalyser (Shimadzu EPMA 8705) with a beam diameter of 1μm, we sometimes observed two luminescence peaks at 410 and 470 nm simultaneously. To investigate the origin of the two bands, we measured cathodoluminescence at room temperature with the higher spatial resolution (Topcon DS130S). We observed that dark spots and dark lines in a CL image of the basal plane and the facets of the InGaN crystals and attributed them to the threading dislocations. We estimate the spatial resolution of the CL measurement is 50 nm compatible with the minimum separation of the dark spots. We observed that smaller crystals with a diameter <1 μm showed a single emission band. The peaks of the single emission bands are identical with neither of the two CL peaks measured by the low-resolution CL equipment. The emission band from each crystal is integrated in the CL band. Summation of the product of the contents of the crystals showing a certain single emission band in the observed area and the efficiency of the band explains the shape of the CL band by the low resolution CL.

L3.53
LOCAL PROPERTIES OF AlN: A COMPUTATIONAL APPROACH. J.M. Vail, Q.C. Qiu and Y. Xu, University of Manitoba, Department of Physics and Astronomy, Winnipeg, MB, CANADA; R. Pandey, H. Jiang, A. Costales and M.A. Blanco, Michigan Technological University, Department of Physics, Houghton, MI.

The optical properties of AlN are significantly affected by point defects. Of particular interest are nitrogen vacancies, in various charge states. The quantitative study of point defects in insulating materials is greatly enhanced by computational analysis. In strongly ionic materials, one can calculate with good confidence such properties as optical absorption and emission, spin densities, local deformation of the crystal, local vibrational mode frequencies, and activation energies for diffusion. The methods used for strongly ionic materials are being adapted for AlN. The model consists of a quantum molecular cluster embedded in a classical crystal, described by the shell model. The quantum-mechanical treatment of the cluster is based on the Hartree-Fock approximation, with Hartree-Fock based pseudopotentials on the boundary. Fractional ionic charges are determined from band-structure analysis, as are basis sets. Perfect-crystal quantum clusters are studied first, centered on aluminum and nitrogen ions respectively. Compatibility amongst the shell-model crystal, the band structure results and the quantum clusters is tested with respect to ionic charges, equilibrium ionic positions, and nearest-neighbor breathing-mode effective force constants. Slight rescaling of polarization atomic orbitals and of nitrogen pseudopotentials is required. These model elements are then applied to the nitrogen vacancy in various charge states.

L3.54
SURFACE TREATMENTS OF GaN STUDIED WITH AFM AND PES. S.M. Widstrand, K.O. Magnusson, E. Moons, L.S.O. Johansson, J.B. Gustafsson, M. Gurnett, Dept. of Physics, Karlstad Univ, Karlstad, SWEDEN; M.I. Larsson, Dept. of Material Sci. and Eng., Stanford Univ, Stanford, CA; H.W. Yeom, Dept of Physics, Yonsei Univ, Seoul, KOREA; H. Miki, Chowa Denko, Chichibu, Saitama, JAPAN; M. Oshima, Dept of Applied Chemistry, Univ of Tokyo, Tokyo, JAPAN.

We present a combined investigation of GaN with Atomic Force Microscopy (AFM) and photoelectron spectroscopy (PES). The goal was to evaluate different cleaning methods, since surface treatments for the cleaning of GaN surfaces is still not well understood. The samples were n-doped GaN(0001), grown by metal organic chemical vapour deposition (MOCVD) on sapphire substrates. The surface treatment methods included vacuum annealing, annealing in ammonia (NH_3), gallium (Ga) adsorption, followed by Ga desorption in a NH_3 flux anneal. Before and after the specific cleaning treatments, we performed PES measurements using synchrotron radiation and imaged the surface by AFM. The AFM images show distinct surface structures, which can be correlated with the sample treatment. The surface structure of as-grown GaN imaged by AFM revealed regular

directional patterns. Specific surface treatments can modify the surface structure drastically. In particular, the combination of Ga-deposition during heating of the sample followed by NH_3 annealing, results in a surprisingly different surface morphology, consisting of 50-100 nm large spherical islands. We have found that surface treatments can indeed improve the surface electronic structure quality, as revealed by sharper features in PES and the surface long-range order, as evident from low energy electron diffraction (LEED) patterns. The PES results showed also saturation effects for NH_3 annealing. The best surface quality, regarding surface contaminations such as oxygen and carbon, was found after Ga adsorption followed by NH_3 flux anneal.

L3.55
COMPARISONS OF GALLIUM NITRIDE AND INDIUM NITRIDE PROPERTIES AFTER CF_4 / ARGON REACTIVE ION ETCHING. Marie Wintrebert-Fouquet, K. Scott A. Butcher, Trevor L. Tansley, Physics Department, Macquarie University, Sydney, AUSTRALIA; Simon K.H. Lam, CSIRO Telecommunications and Industrial Physics, Lindfield, AUSTRALIA.

We present a comparative study of the effects of low power reactive ion etching (RIE) on GaN and InN. This new highly chemical dry etching, using CF_4 and Ar, has been developed for thin nitride films grown at low temperature in our laboratories. GaN films were grown by remote plasma enhanced-laser induced chemical vapor deposition and InN films were grown by radio-frequency reactive sputtering. Optical and electrical characteristics of the films are reported before and after removing 100 to 200 nm of the film surface by RIE. We have previously shown these GaN films, although polycrystalline after growth, may be re-crystallized below the growth temperature. Removal of the surface oxyde has been found to be imperative since a polycrystalline residue remains on the surface after re-crystallization.

L3.56
PHOTOREFLECTANCE CHARACTERIZATION AND CONTROL OF DEFECTS IN GaN BY ETCHING WITH AN INDUCTIVELY COUPLED PLASMA. O.J. Glembocki, D.K. Gaskill, S.M. Prokes, Naval Research Laboratory, Washington, DC; and S.W. Pearton, Department of Material Science and Engineering, University of Florida, Gainsville, FL.

GaN and its alloys are of great interest because of desirable electronic transport properties inherent to these material systems as well as their good thermal dissipation characteristics. A key component of realizing any device is dry etching to define specific structures such as mesas, recessed gates, etc. In dry etching, a combination of energetic ions and a reactive species such as chlorine are used to enhance the process rates and to provide anisotropic etching. A trade-off occurs because the energetic ions can penetrate well below the surface and induce defects such as vacancies or interstitials. In this paper, we have used photoreflectance spectroscopy as a contactless probe electronic damage induced by etching with inductively coupled plasma (ICP) source that utilized Ar and chlorine. The photoreflectance (PR) technique traditionally provides band structure information also allows us to obtain information about the response of the GaN surfaces to the AC photovoltage that is used to modulate the built-in electric fields. Thus the PR intensity is a direct measure of the surface photovoltage. We have studied the electronic damage as a function of ion energy. We find that the use of an Ar only plasma leads to significant reductions in the photovoltaic response at ion energies as low as 50V. The addition of chlorine to the plasma leads to significant improvements in the levels of damage. In this case, we find that significant damage does not occur until 300V. In addition, we have found that the quality of the starting GaN surface has a significant effect on the levels of damage that is produced by ICP etching. Our PR results have been correlated to AFM images of the etched surfaces. From this work, we can develop a complete picture of the nature of the ICP etched surface.

L3.57
ELECTROREFLECTANCE AND PHOTOREFLECTANCE STUDIES OF ELECTRIC FIELDS IN Pt/GaN SCHOTTKY DIODES AND AlGaN/GaN HETEROSTRUCTURES. S. Shokhovets, G. Goldhahn, G. Gobsch, Ilmenau Technical Univ, Inst of Physics, Ilmenau, GERMANY; O. Ambacher, Ilmenau Technical Univ, Center for Micro- and Nanotechnologies, Ilmenau, GERMANY; I.P. Smorchkova, J.S. Speck, U. Mishra, Univ of California, Electrical and Computer Engineering Dept and Materials Dept, Santa Barbara, CA; A. Link, M. Hermann, M. Eickhoff, Technical Univ Munich, Walter Schottky Inst, Garching, GERMANY.

A detailed investigation of electric fields caused by Schottky contacts or the large pyroelectric polarization of wurtzite group III nitrides is crucial to understand the physical properties and performance of GaN based heterostructures and devices. Among the methods suitable for a direct measurement of the electric field strength, electroreflectance (ER) and photoreflectance (PR) have proven their high sensitivity and usefulness. However, reports on systematic applications of these methods to nitrides are rare up to date. We have investigated Pt/GaN Schottky diodes of N- and Ga-face polarity as well as AlGaN/GaN heterostructures confining polarization induced two-dimensional electron gases. Three main mechanisms of electro-optical response, (a) Franz-Keldysh oscillations, (b) electric field-dependent contribution of excitons and excitonic continuum to the dielectric function, and (c) linear electro-optic (LEO) effect were experimentally investigated. An exciton dead layer leading to so called rotation ER spectra and a large signal far below the absorption edge due to the LEO effect were observed in GaN Schottky diodes. In addition an unexpected strong temperature dependence of the polarization induced electric field in the barrier of undoped AlGaN/GaN heterostructures was measured. Analysis of the data was carried out using electric field-dependent dielectric functions of epitaxial GaN and AlGaN layers. Inhomogeneities in the electric fields were taken into account by considering a space charge region by a system of thin sub-layers with a homogeneous electric field within each of them. A comparison of calculated reflectance, ER and PR spectra with the experimental data yields an electric field strength that, in general, increases with increasing temperature. Other quantities, such as exciton energies corresponding to zero-field conditions and Schottky barrier height for the case of diodes were determined as well. The results are discussed in terms of temperature dependent ionized impurity concentrations for N- and Ga-polarity samples as well as in dependence on free carrier screening of polarization induced surface charges.

L3.58
INVESTIGATION OF INTERFACE DEFECT STATE DENSITY AND BAND OFFSET OF GaN-Ga_2O_3-SiO_2 AND GaN-Si_3N_4 SYSTEMS AFTER LOW TEMPERATURE N_2/He PLASMA-ASSISTED SURFACE CLEANING. C. Bae and G. Lucovsky, Dept of Physics, Materials Science and Engineering and Electrical and Computer Engineering, North Carolina State Univ, Raleigh, NC.

GaN has emerged as important material for opto-electronic and high temperature/high power device application. This paper compares SiO_2 and Si_3N_4, which have been the most widely and deeply studied gate dielectric insulators, from the viewpoint of interface defect state density and band offset with GaN. After remote N_2/He plasma treatment of GaN surface at low temperature (~300 °C), there is no detectable C and Cl, and only a very small residual O atom signal (~0.1 monolayer of oxygen coverage on GaN surface). To overcome subcutaneous oxidation of GaN which oxidizes a few monolayer of the underlying substrate during remote plasma enhanced deposition of SiO_2, two different approaches were used: the interface and dielectric layer are formed i) by a two-step process that provides separate and independent control of the interface, an ultra-thin GA_2O_3 interfacial oxide using remote plasma-assisted oxidation of GaN and the SiO_2 dielectric, and ii) by direct deposition of Si_3N_4 on GaN. The interface defect state density (or band offset) of two different systems, GaN-GA_2O_3-SiO_2 and GaN-Si_3N_4, were investigated using capacitance-voltage (or current-voltage) measurement of metal-insulator-semiconductor (MIS) capacitors as a function of the insulator thickness and temperature.

L3.59
BAND OFFSET MEASUREMENTS OF Si_3N_4 ON CLEAN N-TYPE GaN. Ted E. Cook Jr., C.C. Fulton, W.J. Mecouch, R.F. Davis, G. Lucovsky, and R.J. Nemanich, Dept. of Materials Science and Engineering and Dept. of Physics, North Carolina State University, Raleigh, NC.

The investigation of the band alignment of the Si_3N_4-GaN interface is important for passivation of high voltage devices and possibly for gate insulator applications. In this study X-ray and UV photoelectron spectroscopy were used to measure the electronic states as Si_3N_4 was deposited on clean GaN surfaces. The n-type GaN ($5x10^{18}$ cm^{-3}) surface was atomically cleaned in NH_3 at 860°C, and the surface showed upward band bending of ~0.2 ± 0.1 eV with an electron affinity of 3.1 ± 0.1 eV. Layers of Si (~0.2 nm) were deposited on the clean GaN which were nitrided using an ECR N_2 plasma at 300°C and subsequently annealed at 650°C for densification of the Si_3N_4 film. Surface analysis was performed after each step in the process, and yielded a valence band offset (VBO) of ~0.6eV, where the valence band of the GaN lies 0.6 eV below the Si_3N_4 valence band. The conduction band offset (CBO) of ~2.2 eV is deduced from the measurement of the VBO and knowledge of the respective bandgaps. These values are in relative agreement with the predicted values of 0.3 eV and 1.9 eV for the VBO and CBO obtained from the charge neutrality level (CNL) model of the heterojunction interface.

L3.60
EFFECTS OF PLASMA CONDITIONS ON STRUCTURAL AND ELECTRICAL BEHAVIOR OF MAGNESIUM OXIDE GATE DIELECTRICS GROWN BY GSMBE ON GALLIUM NITRIDE.

A.H. Onstine, B.P. Gila, C.R. Abernathy, S.J. Pearton, University of Florida, Dept of Materials Science and Engineering, Gainesville, FL; J. Kim, F. Ren, University of Florida, Dept of Chemical Engineering, Gainesville, FL.

Fabrication of high performance metal oxide semiconductor field effect transistors (MOSFETs) on gallium nitride will require both good interfacial electrical characteristics and good breakdown voltage. The wide band gap of magnesium oxide in conjunction with its high melting point make it an ideal prospect as a new gate dielectric for use in III-Nitride based high temperature or high power devices. In this paper we report on the effects of the oxygen plasma source and settings on the structural and electrical properties of MgO grown by GSMBE. Magnesium oxide was deposited using an elemental Mg source and either an electron cyclotron resonance (ECR) oxygen plasma at 2.54 GHz, or a radio frequency (RF) oxygen plasma at 13.56 MHz. Using either source, the MgO film first deposits epitaxially at the GaN interface and then becomes poly-crystalline as shown by RHEED and TEM. It is the single crystal layer which is believed to be responsible for the relatively low interface state densities, ~1-4 x 10^{11} cm^2/eV, which are observed using this material. The breakdown field strength, however, can vary considerably depending upon the growth conditions. In general, RF grown oxides show superior breakdown fields than those grown with the ECR plasma. This is believed to be due at least in part to the smoother surface morphology obtained with the RF plasma. Using the RF plasma, further improvements in breakdown voltage were obtained using lower oxygen pressures, with the highest E_{BD} of 3.7MV/cm obtained using this approach. Both of these results suggest that the improvement may be due to an increase in the average ion energy. Preliminary experiments varying the ion energy for fixed oxygen pressure appear to confirm this. Possible models to explain this dependence on ion energy will also be discussed.

SESSION L4: EPITAXY—NONPOLAR ORIENTATIONS AND ALLOYS
Chair: James S. Speck
Tuesday Morning, December 3, 2002
Room 302 (Hynes)

8:30 AM L4.1
MORPHOLOGY AND SURFACE RECONSTRUCTIONS OF M-PLANE GaN. C.D. Lee and R.M. Feenstra, Dept. Physics, Carnegie Mellon University, Pittsburgh, PA; J.E. Northrup, Palo Alto Research Center, Palo Alto, CA; L. Lymperakis and J. Neugebauer, Fritz-Haber-Institut der Max-Planck-Gesellschaft, Berlin, GERMANY.

Growing GaN along the (10$\bar{1}$0) axis (in contrast to the commonly employed growth along (0001)) has the advantage that spontaneous or piezoelectric fields are absent. While the surface structures of polar GaN (0001) and (000$\bar{1}$) and their effect on the growth morphology are now well understood little is known regarding the atomic structure and morphology of the non-polar (10$\bar{1}$0) surfaces. We have therefore studied these surfaces by scanning tunneling microscopy and first principles calculations. GaN(10$\bar{1}$0) surfaces have been grown by plasma assisted molecular beam epitaxy on ZnO (10$\bar{1}$0) substrates. A low-temperature GaN buffer layer is found to be necessary to obtain good structural quality of the films; a 20 nm thick GaN layer is grown at 500 C, and subsequent growth was performed at 700-750 C. Reflection high energy electron diffraction shows a streaky 1x1 pattern throughout the entire growth sequence when Ga-rich conditions are used, whereas growth under N-rich conditions resulted in spotty patterns indicative of 3-dimensional growth. Well oriented (10$\bar{1}$0) GaN films (i.e. m-plane surfaces) are obtained. For thicker films we observe the formation of (10$\bar{1}$1) facets. Several reconstructions of the GaN(10$\bar{1}$0) surfaces are observed by scanning tunneling microscopy. The most dominant of these occurs under Ga-rich conditions and consists of corrugation rows extending at angles of ±7 degrees to the [0001] direction. A structural subunit of this reconstruction has surface unit cell of 4x5, with the entire unit cell being 21x20. Relatively little difference is found between the empty and filled states images, and imaging at low voltages is found to be possible, thus indicating that this surface is metallic. To identify this reconstruction first-principles pseudopotential density functional theory calculations have been performed. The calculations indicate that in the Ga-rich limit it is energetically favorable to cover the surface with a bilayer of Ga. We propose that the 21x20 structure observed experimentally consists of a contracted and distorted arrangement of a Ga bilayer on the surface. This work has been supported by the Office of Naval Research under grant N00014-96-1-0214 (program monitor, C. Wood) and by the EC-TMR project "IPAM".

8:45 AM L4.2
GaN EPILAYERS AND AlGaN/GaN MULTIPLE QUANTUAM WELLS ON FREE-STANDING (1$\bar{1}$00) ORIENTED GaN SUBSTRATES. C.Q. Chen, M.E. Gaevski, W.H. Sun, E. Kuokstis, J.W. Yang, G. Simin, M.A. Khan, Department of Electrical Engineering, University of South Carolina, Columbia, SC; Herbert-Paul Maruska, David W. Hill, Mitch M.C. Chou, Bruce Chai, Crystal Photonics, Inc., Sanford, FL.

To date nearly all the reported III-N devices have used basal plane (0001) sapphire, 6H or 4H-SiC, or freestanding (0001) GaN substrates. In this substrate orientation built-in electrostatic fields from the spontaneous and piezoelectric polarizations strongly influence the device characteristics. For high electron mobility transistors these fields give rise to 2D electron gas. For light emitting diodes the built in field degrades the emission characteristics due to a separation of the electron-hole wave functions. To clearly establish the role of polarization fields we for the first time present a comprehensive study of GaN layers and GaN-AlGaN multiple quantum wells over c-plane and M-plane GaN substrates. In the same growth run homo-epitaxial GaN films and GaN-AlGaN multiple quantum wells (MQWs) were grown on (0001) GaN coated basal plane sapphire and freestanding (1$\bar{1}$00) oriented (M-plane) GaN substrates using low-pressure metalorganic chemical vapor deposition. The freestanding M-plane GaN layers (100-300 μ thick) were grown by HVPE over LiAlO2 substrates, which post growth, were removed by wet chemical etching. Scanning electron microscopy, atomic-force microscopy and photoluminescence were used to study the influence of growth conditions such as the V/III molar-ratio and temperature on the surface morphology and optical properties of the epilayers. The M-plane grown MQWs have a very smooth surface morphology and the do not exhibit etch pits indicating an absence of threading dislocations in the growth direction. Their PL signals are a factor of 30 higher than those for identical structures over (0001) GaN over sapphire. In addition the PL signals show no blue shift with increasing excitation powers clearly indicating an absence of built in electric field from the spontaneous and piezoelectric polarizations. Since the M-plane also offers perpendicular cleavage planes, our work forms the basis of fabricating high power light emitting diodes and lasers for white light generation.

9:00 AM L4.3
CHARACTERIZATION OF NONPOLAR (11$\bar{2}$0) a-PLANE AlGaN/GaN AND InGaN/(In)GaN QUANTUM STRUCTURES. Michael D. Craven, Tal Margalith, Stacia Keller, Patrick Waltereit, Feng Wu, James S. Speck, Steven P. DenBaars, Materials Department, University of California, Santa Barbara, CA.

Growth on nonpolar wurtzite nitride semiconductor surfaces provides a promising means of eliminating polarization-induced electric field effects in nitride-based optoelectronic and electronic devices. Current nitride technology employs heterostructures grown along the polar [0001] direction that possess strong electrostatic fields parallel to the growth direction. The internal fields present in c-plane quantum structures tilt energy bands, thereby spatially separating electron and hole wavefunctions, and red-shifting the emission energy. Conversely, these internal fields will not affect nonpolar nitride quantum structures since there is no polarization along a nonpolar growth direction. Continuous nonpolar (11$\bar{2}$0) a-plane GaN films grown on (1$\bar{1}$02) r-plane sapphire substrates via metalorganic chemical vapor deposition served as template layers for the growth of nonpolar AlGaN/GaN and InGaN/(In)GaN quantum structures. AlGaN/GaN superlattices (SLs) with Al compositions between 7% and 40% and AlGaN thickness between 5 nm and 11 nm were analyzed. Clearly defined satellite peaks were observed in 2θ-ω x-ray diffraction scans indicating the presence of abrupt SL interfaces. Photoluminescence (PL) measurements revealed consistent 3.45 eV band edge emission for all nonpolar SLs studied, regardless of AlGaN thickness or composition. Inconsistent red-shifting of the band edge emission would be expected if polarization-induced fields were affecting the a-plane SLs. In contrast to the AlGaN/GaN SL emission characteristics, increasing the nominal well thickness of nonpolar $In_{0.1}GaN/In_{0.03}GaN$ multiple quantum well structures from 1.5 nm to 5 nm caused an increase in the PL peak emission wavelength and intensity. The 12 nm increase in emission wavelength is expected for nonpolar wells that follow a flat-band model while the seven-fold increase in emission intensity indicates that electron-hole wavefunction overlap does not degrade with increasing well width as commonly observed for polar wells subject to internal fields. The work described above will be further augmented with self-consistent Poisson-Schrodinger calculations of the emission characteristics and transmission electron microscopy analysis of the structural quality.

9:15 AM L4.4
A COMPARATIVE STUDY OF GROWTH AND LUMINESCENCE PROPERTIES OF InGaAlN ALLOYS AND GaN/InGaAlN MQWS GROWN BY MBE ON M-PLANE GaN SUBSTRATES (NON-POLAR) AND C-PLANE GaN QUASI-SUBSTRATES (POLAR). A. Bhattacharyya, J. Cabalu, Tai-Chou Chen, Y.

Fedyunin, T.D. Moustakas, Boston University, Department of Electrical Engineering, Boston, MA; I. Friel, Boston University, Physics Department, Boston, MA; H.-P. Maruska, D.W. Hill, J.J. Gallagher, M.M. Chou, B. Chai, Crystal Photonics Inc., Sanford, FL.

The majority of III-nitride materials and devices have been grown on substrates such as c-plane sapphire or 6H-SiC, leading to growth along the polar [0001] direction. This gives rise to large electric fields across MQWs due to polarization effects. Consequently, light emitting devices suffer from longer radiative recombination times, reduced quantum efficiency and red-shift of the emission wavelength. These problems can be overcome by growing device structures along a non-polar direction such as [10-10]. In this paper we report on a comparative study of the growth and luminescence properties of bulk quaternary alloys and MQWs on M-plane GaN (10-10) freestanding substrates and (0001) HVPE-grown GaN quasi-substrates by plasma-assisted MBE. Our results indicate that bulk quaternaries exhibit enhanced luminescence intensities compared to ternaries, possibly due to compositional inhomogeneities as indicated by panchromatic cathodoluminescence. Also MQWs with GaN wells and AlInGaN barriers exhibit stronger luminescence than similar structures with ternary AlGaN barriers, a result we attribute to the surfactant effect of indium, leading to smoother interfaces. A series of AlInGaN/GaN MQW structures with different well widths were grown on M-plane GaN and c-plane GaN and a comparison of the structural and luminescence properties performed using XRD, PL and CL. Our results show that the luminescence peak of MQWs grown on c-plane GaN is red-shifted compared to similar structures grown on M-plane GaN, with the shift increasing with well width, a result attributed to the quantum-confined Stark effect. Furthermore, the luminescence intensity falls sharply for wider wells in the structures grown on c-plane GaN. However, for the structures grown on M-plane GaN, the photoluminescence intensity increases only slightly with well width. For wider wells, the photoluminescence of MQWs grown on M-plane GaN is 20 times more intense than a similar structure grown on c-plane GaN

9:30 AM L4.5
GROWTH OF QUATERNARY AlInGaN/GaN HETEROSTRUCTURES BY PLASMA-ASSISTED MBE.
Eva Monroy, Edith Bellet-Amalric, Yuji Hori, Denis Jalabert, Noelle Gogneau, Fabrice Enjalbert, Le Si Dang, Bruno Daudin, CEA-Grenoble, Equipe mixte CEA-CNRS-UJF Nanostructures et Semiconducteurs, FRANCE.

The major motivation for quaternary alloy studies is the possibility to cancel the electric field in the active region of heterostructures. However, the growth of quaternary compounds is a challenge, due to different bonding lenght and optimal growth temperature of respective binary compounds. Using sophisticated techniques for quaternary growth by MOVPE, the feasibility of AlInGaN has been demonstrated. By contrast, the low temperature capabilities of MBE growth open new possibilities for the elaboration of quaternary-based heterostructures in the whole composition range. In this work we demonstrate the capability of plasma-assisted MBE for the growth of quaternary $Al_xIn_yGa_{1-x-y}N(0\leq x\leq 1,\ 0\leq y\leq 20)$/GaN heterostructures.
Structures were grown by plasma-assisted MBE on SiC and GaN templates. Consistent with RBS measurements, it is concluded that Al mole fraction is directly determined by the Al flux and can be checked in situ by RHEED oscillation measurements during AlN growth. Then, for a given Al mole fraction, the maximum In incorporation is governed by the substrate temperature, similarly to InGaN growth. It is furthermore demonstrated that for a given substrate temperature, the maximum In content than can be incorporated in AlGaN decreases drastically for increasing Al mole fractions. For the range of substrate temperatures under study (590-650°C), two-dimensional growth has been achieved under In rich conditions, in presence of a dynamically-stable In film on the sample surface.
The structural quality of the quaternary alloy was demonstrated by the reduced broadening both in symmetric and asymmetric reflections in High resolution X-ray diffraction. A FWHM of 6 arc-min is obtained for the (0002) X-ray diffraction peak in the ω-scan for $Al_{0.36}In_{0.11}Ga_{0.53}N$ layers, which reproduces the broadening of the GaN template. Optical emission was analyzed by reflectivity and photoluminescence (PL). Intense PL emission is observed in absence of deep level recombination. An unexpectedly large bandgap bowing parameter, about 5 eV, was measured when varying the In mole fraction.

10:15 AM L4.6
LATTICE RELAXATION OF AlN BUFFER ON SURFACE-TREATED SiC IN MOLECULAR-BEAM EPITAXY FOR GROWTH OF HIGH-QUALITY GaN. Jun Suda, Kouhei Miura, Misako Honaga, Norio Onojima, Yusuke Nishi, Hiroyuki Matsunami, Kyoto Univ, Dept of Electronic Science and Engineering, Kyoto, JAPAN.

Growth of high-quality GaN on SiC is one of key issues to realize high-frequency high-power transistors. We have reported high-quality molecular beam epitaxial (MBE) growth of AlN on SiC substrates pretreated by high-temperature HCl-gas etching.[1] In this study, the AlN layer was used as a buffer layer for GaN growth. We discuss the correlation between the lattice relaxation process of AlN buffer, which depends on surface reconstruction of SiC substrates, and the quality of GaN layer grown on the AlN buffer. SiC substrates were thermally etched using HCl gas in a SiC chemical vapor deposition reactor, which resulted in step-and-terrace structure with $(\sqrt{3}\times\sqrt{3})$R30° surface reconstruction. Successively, some of the substrates were processed by wet chemical treatment using HF solution. The substrates also had step-and-terrace structure, but exhibited (1×1) structure. The AlN buffer and GaN main layers were grown on these substrates by plasma-assisted MBE. The lattice relaxation of AlN was monitored by *in – situ* reflection high-energy electron diffraction (RHEED). In the growth of AlN on $(\sqrt{3}\times\sqrt{3})$R30° SiC surface, the in-plane lattice constant of AlN approached that of bulk AlN quickly. On the other hand, AlN grown on (1×1) SiC surface exhibited slow relaxation. Even after 60-nm-thick growth, the layer still had a strong compressive strain. In the both cases, the RHEED patterns of grown layers were streaky, indicating flat surfaces. The full width at half maximum of (0002) X-ray rocking curve for 1μm-thick GaN on $(\sqrt{3}\times\sqrt{3})$R30° SiC was ranging from 700-1700 arcsec. Whereas, GaN on (1×1) SiC exhibited typically 100 arcsec (best: 70arcsec), which is considerably small in MBE-grown GaN on SiC. The number of spiral growth hillocks was 10^7 cm^{-2}, which is two-order of magnitude smaller than that of GaN grown on a SiC substrate without special surface treatment.
[1] N. Onojima, J. Suda and H. Matsunami, Appl. Phys. Lett. **80**, 76 (2002).

10:30 AM L4.7
EFFECTS OF LOW-TEMPERATURE AlN BUFFER-LAYER AND STRAIN-LAYER SUPERLATTICE ON DENSITY OF THREADING DISLOCATIONS IN AlGaN LAYERS. H. Meidia, D.-W. Kim, S. Mahajan, Arizona State University, Dept of Chemical and Materials Engineering, Tempe, AZ; C.Q. Chen, J.P. Zhang, J.W. Yang, M.A. Khan, University of South Carolina, Dept of Electrical Engineering, Columbia, SC.

To study the effects of low temperature (LT) AlN buffer layers and strain-layer superlattices (SLs) on the density of threading dislocations (TDs) in AlGaN layers, we grew two types of samples using metal organic chemical vapour deposition. The first sample consisted of four periods of LT-AlN/AlGaN layers grown on sapphire. The second sample contained the strained AlN/AlGaN SLs on GaN/LT-AlN/AlGaN layers. These samples were analysed using transmission electron microscopy. We show that the insertion of four LT-AlN buffer layers placed between the AlGaN layers is moderately effective in reducing TDs density. The density of TDs on the third AlGaN layer is $\sim 5\times10^9$/cm^2 and after the incorporation of the fourth LT-AlN buffer layer the density of TDs is reduced to $\sim 2\times10^9$/cm^2. Most of these TDs are a type that is propagated through the LT-AlN buffer layer. We also show that the LT-AlN buffer layer that was deposited on GaN layer introduces more TDs density in AlGaN overgrowth. The strained SLs that was grown after the AlGaN layer does not have any effect on the density of TDs. The support for these works by AFOSR is gratefully acknowledged.

10:45 AM L4.8
KINETICS OF THE GROWTH OF GALLIUM NITRIDE BY METALORGANIC MOLECULAR BEAM EPITAXY. Isaiah Steinke, Department of Chemical Engineering and Materials Science, University of Minnesota, Minneapolis, MN; Phil Cohen, Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis, MN.

The differences in the growth kinetics of GaN films grown by molecular beam epitaxy (MBE) and metalorganic chemical vapor deposition (MOCVD) are partially due to the different growth regimes as well as the uncertainty in the reported results. For example, at the cross-over point between Ga-rich and N-rich growth, there are different reports of surface smoothening. Moreover, observations of RHEED intensity oscillations on the two surface polarities are different and sometimes irreproducible. To examine these kinetics, GaN films were grown homoepitaxially and heteroepitaxially by metalorganic molecular beam epitaxy (MOMBE) using trimethylgallium (TMGa) and ammonia (NH_3) as sources. Two *in situ* techniques were used to examine the surface structure and morphology at different growth conditions: dynamical reflection high-energy electron diffraction (RHEED) and scanning tunneling microscopy (STM) after quenching the sample. The influence of Ga/N flux ratio and ammonia pressure on the film morphology and surface reconstruction was studied. These parameters were found to control step bunching vs hillock growth modes – when the critical length for hillock formation was larger than the distance between steps, step

flow modes were observed. Growth on the N and Ga polarities were found to be very different; a phase map is presented for the N polarity that is very different from MOCVD results. Defects are found to affect the apparent period of the growth.

11:00 AM L4.9
ULTRAHIGH-QUALITY AlN EPILAYERS OVER SAPPHIRE WITH ROOM TEMPERATURE BAND-EDGE PHOTO-LUMINESCENCE AT 208 NM. Jianping Zhang, H.-M. Wang, E. Kuokstis, Q. Fareed, W.H. Sun and M. Asif Khan, Department of Electrical Engineering, University of South Carolina, Columbia, SC.

We report on the low-pressure metal organic chemical vapor deposition (MOCVD) of ultrahigh quality AlN epilayers over basal-plane sapphire substrates. Selecting growth conditions with extremely low V/III ratios to minimize the premature gas-phase reactions and the growth temperatures in excess of 1050 °C to enhance the Al-adatoms surface migration, we significantly improved the epitaxy quality. For 0.3 μm thick AlN layers on c-plane sapphire substrates, the full width at half maximum (FWHM) values for the (002) and (114) X-ray diffraction (XRD) rocking curve peaks were measured to be respectively less than 60 and 250 arcsecs. AFM measurements showed the films to have an atomically smooth surface with an RMS surface roughness of 5 Å.The films also exhibited strong room temperature (RT) band-edge photoluminescence (PL) peaked at 208 nm. The strength and the line width of the PL signal were nearly identical to those measured for c-plane oriented bulk AlN crystals. The high-quality AlN epilayer was then used as a buffer for the deposition of AlN/AlxGa1-xN quantum wells. These quantum wells, in spite of the strong polarization-related electric fields, exhibited a strong band-to-band RT PL emission at 230 nm. To the best of our knowledge this is the first ever report of RT PL emission below 250 nm from an AlN/AlGaN quantum well structure. Growth details and material characterization results will be presented to establish the feasibility of our high quality AlN layers and AlN/AlGaN quantum wells for deep UV light emitting diodes (LEDs) with emissions in the 200-280 nm range.

11:15 AM L4.10
GROWTH OF THICK InN BY MOLECULAR BEAM EPITAXY. Hai Lu, William J. Schaff, Lester F. Eastman, Dept. of Electrical and Computer Engineering, Cornell University, Ithaca, NY; David C. Look, Semiconductor Research Center, Wright State University, Dayton, OH; J. Wu, Wladek Walukiewicz, Lawrence Berkeley National Laboratory, Berkeley, CA; Richard J. Molnar, MIT Lincoln Laboratory, Lexington, MA.

The successful demonstration of the narrow bandgap (0.7 eV) of InN has important implications. [1] III-nitride-based light emitters can be made over a broad wavelength range from infrared to ultraviolet. There is an important need to synthesize high quality InN for the extraction of its fundamental parameters. In this study, InN films with thickness up to 10 μm were prepared by molecular beam epitaxy on (0001) sapphire and quasi-bulk GaN templates. Previously it has been challenging to grow InN beyond 1 μm because the growing surface tended to become rough near 1 μm of thickness. Techniques to overcome this limit have been developed. Various buffer techniques were used and compared to optimize the epitaxial growth. The thick InN films were characterized by x-ray diffraction, reflective high-energy electron diffraction, atomic-force microscopy, photoluminescence and Hall measurements. It was found that with increasing film thickness, the Hall mobility will monotonically increase while carrier concentration decreases. Hall mobility beyond 2000 cm^2/Vs with carrier concentration below 4×10^{17} cm^{-3} was obtained at room temperature. Compared with the lowest carrier concentration $\sim2\times10^{18}$ cm^{-3} obtained on thin InN films grown at the same condition, the conclusion is that impurities from the growth environment are not responsible for the high background doping of InN. Instead, some structural defects, or substrate/buffer impurities, may be the major source of the unintentional doping, which can be reduced by growing thicker films. Scattering mechanisms will be discussed to explain the evolution of Hall mobility at different temperatures. [1] J. Wu, W. Walukiewicz, K. M. Yu, J. W. Auger III, E. E. Haller, Hai Lu, William J. Schaff, Yoshiki Saito, Yasushi Nanishi, "Unusual properties of the fundamental band gap of InN." Appl. Phys. Lett. (2002), 80(21), 3967-3969.

11:30 AM L4.11
GROWTH AND APPLICATIONS OF SiCAlN ON Si(111) VIA A CRYSTALLINE OXIDE INTERFACE. John Tolle, Radek Roucka, P.A. Crozier, A.V.G. Chizmeshya, I.S.T. Tsong and J. Kouvetakis, Arizona State University, Tempe, AZ.

Growth of single-phase SiCAlN epitaxial films with the wurtzite structure is conducted directly on Si(111) despite the structural differences and large lattice mismatch (19%) between the two materials. Commensurate heteroepitaxy is facilitated by the conversion of native and thermally grown SiO_2 layers on Si(111) into crystalline oxides by in situ reactions of the layers with Al atoms and the H_3SiCN precursor, forming coherent interfaces with the Si substrate and the film. High-resolution transmission electron microscopy (TEM) and electron energy loss spectroscopy (EELS) show that the amorphous SiO_2 films are entirely transformed into a crystalline Si-Al-O-N framework in registry with the Si(111) surface. This crystalline interface acts as a template for nucleation and growth of epitaxial SiCAlN. With a 3.2 eV band gap, applications of SiCAlN include its use as a buffer layer to replace the highly resistive AlN buffer layer current used to grow GaN on Si substrates. Integration of wide bandgap semiconductors with Si is readily achieved by this process.

11:45 AM L4.12
X-RAY DIFFRACTION AND RAMAN STUDY OF HIGH QUALITY GaN PRODUCED BY ULTRA HIGH RATE MAGNETRON SPUTTER EPITAXY. Minseo Park, J-P. Maria, J.J. Cuomo, Department of Materials Science and Engineering, North Carolina State University, Raleigh, NC; Y.C. Chang, J.F. Muth, R.M. Kolbas, Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC; R.J. Nemanich, Department of Physics, North Carolina State University, Raleigh, NC; E. Carlson, J. Bumgarner, Kyma Technologies, Inc., Raleigh, NC.

Thick films of GaN were studied using X-ray diffraction and Raman spectroscopy. The GaN thick films were deposited on (0001) sapphire using novel ultra high rate magnetron sputter epitaxy with typical growth rates as high as 10-60 μm/min. The width of the X-ray rocking curve from the (0002) reflection for the sample produced by this technique is ~300 arc-sec, which is unprecedented among GaN produced by a sputtering-type process. Our recent sample shows an X-ray rocking curve width of 240 arc-sec. Only the allowed modes were observed in the polarized Raman spectra. The background free carrier concentration is lower than $3*10^{16}$ cm^{-3}. The phonon lifetime of the Raman E2(2) mode of the sputtered GaN was comparable to that of the bulk single crystal GaN grown by sublimation. The quality of the film was uniform across the wafer. The film was thermally stable upon annealing in N2 ambient. The X-ray and Raman analysis revealed that the sputtered GaN films are of high crystal quality.

SESSION L5: OPTICAL PROPERTIES
Chair: Steve A. Stockman
Tuesday Afternoon, December 3, 2002
Room 302 (Hynes)

1:30 PM *L5.1
GaN/AlGaN HETEROSTRUCTURES FOR OPTOELECTRONICS DEVICES BASED ON INTERSUBBAND TRANSITIONS. Claire Gmachl, Hock M. Ng, Jörg D. Heber, and Alfred Y. Cho, Bell Laboratories, Lucent Technologies, Murray Hill, NJ; S.N. George Chu, Agere Systems, Murray Hill, NJ.

Optical devices, primarily lasers and photo-detectors, based on intersubband (IS) transitions in GaAs- or InP-based multiple quantum well (MQW) structures are well established. These devices operate predominantly in the mid-and far-infrared range of the electromagnetic spectrum as their band-discontinuities do not allow for shorter wavelength applications. Larger band-discontinuities are known to be present in several Sb-based materials, II-VI compounds, and GaN-based heterostructures. In particular the latter are of growing interest due to several factors: the ability to reach the fiber optic wavelength range at 1.3 - 1.55 um through IS transitions, material parameters, such as a high effective electron mass and a large optical phonon energy, that provide an intrinsically ultrafast electron dynamics, the rapidly growing knowledge surrounding this material system, and its already established commercial impact in blue light emitting diodes and lasers as well as high power transistors. In this talk, we present measurements on IS-transitions in the communications wavelength range in GaN/AlGaN heterostructures. The wurtzite-type MQW samples were grown by molecular beam epitaxy (MBE) on various orientation sapphire substrates with GaN and AlGaN templates of varying composition and thickness. Three types of samples were grown, stacks of single QWs with bulk-like barriers, single QWs with superlattice (SL)-type barriers, and coupled double QWs (DQWs) with SL barriers. IS-absorption at wavelengths of 1.44, 1.41, and 1.52 um are measured for 1.1, 1.2, and 1.3 nm wide GaN QWs with Al0.85Ga0.15N barriers, respectively. Peak absorption wavelengths as short as 1.35 um and 1.52 um were measured for a symmetric DQW of 1.2 nm wide wells coupled by a 1.0 nm wide barrier, which also showed evidence of excited-state anti-crossing. Asymmetric DQWs display no such anti-crossing, and the ground-state anti-crossing energies were found to be much smaller than the energy broadening of individual transitions. Conventional time resolved pump-probe spectroscopy confirmed ultrafast electron relaxation times between the subbands of few 100 fs.

2:00 PM L5.2
OPTICAL PROPERTIES OF ORDERED AlGaN. Martin Albrecht, M. Benamara, H.P. Strunk, Universität Erlangen Nürnberg, Institut für Werkstoffwissenschaften, Lehrstuhl Mikrocharakterisierung, Erlangen, GERMANY; L. Kirste, D.G. Ebling, K.W. Benz, Freiburger, Materialforcshungszentrum, Universität Freiburg, Freiburg, GERMANY; I. Grzegory, S. Porowski, Polish Academy of Sciences, High Pressure Research Centre, Warsaw, POLAND; A. Kaschner, A. Hoffmann, Institut für Festkörperphysik, Technische Universität Berlin, Berlin, GERMANY.

Classical III-V semiconductors (e.g. GaInP) under certain growth conditions form natural monoatomic superlattices. The formation of this type of superlattice leads to reduction in crystal symmetry and essentially influences the optical properties. The most prominent changes are a reduction in the fundamental band gap and a valence band splitting. While ordering in clasisical III-V semiconductors is well studied both experimentally and theoretically, only very few studies exist on ordering in III-Nitrides.
In this paper we present a study on structural and optical properties of ordered AlxGa1-xN alloys (0<x<1). The layers were grown by radio frequency plasma enhanced molecular beam epitaxy onto sapphire substrates. Depending on growth conditons an alternating AlN/GaN superlattice forms that reduces the lattice symmetry from the P63mc wurtzite symmetry to P3m1. The superlattice has been evidenced by x-ray diffraction, Raman spectroscopy and electron diffraction. The degeree of odering was quantified by (0001) superlattice reflection by both x-ray and electron diffraction. Our analsyis shows that he degree of ordering increases with increasing growth temperature. Transmission electron diffraction shows that the odering appears in form of ordered domains with a thickness of 3-10 nm and lateral extension of 100 nm. The size of the domains can be clearly correlated with the surface topology. The degree of order and the size of the ordered domains increases from the interface towards the surface of the layer.
Annealing under high pressure and high temperature leads to disappearance of the natural superlattice. This proves that the superlattice is unstable in the bulk: It is induced due to surface thermodynamics.The comparison of CL spectra of annealed and as grown samples shows a blue shift by 280 meV of the annealed sample with respect to the ordered one (for an Al0.5Ga0.5N). A comparison of annealed and as grown samples over the whole range of composition shows that annealed samples show no band gap bowing, while ordered ones have a bowing coefficient of 2.3 eV. Our results show that ordering in III-nitrides has very similar effects on optical properties as in classical III-V semicondutcors. in consequence ordering can be used as an additional degree of freedom to tailor the band structure of III-nitrides.

2:15 PM L5.3
ROLE OF POLARIZATION IN THE PHOTOLUMINESCENCE OF C- AND M-PLANE ORIENTED GaN/AlGaN MULTIPLE QUANTUM WELLS. Edmundas Kuokstis, Changqing Chen, Mikhail Gaevski, Wenhong Sun, Jinwei Yang, Grigory Simin, and M. Asif Khan, Univ of South Carolina, Dept of Electrical Engineering, Columbia, SC; Herbert-Paul Maruska, David W. Hill, Mitch M.C. Chou, Bruce Chai, Crystal Photonics, Inc., Sanford, FL.

We present a comparative study of excitation-dependant photoluminescence (PL) of wurtzite-type GaN/AlGaN multiple quantum wells (MQWs) over GaN coated [0001]-sapphire (C-plane) and single crystalline [1$\bar{1}$00]-oriented freestanding GaN (M-plane) substrates. The 350- μm-thick M-plane (GaN) templates were grown by hydride phase epitaxy on the closely lattice matched (100) plane of $LiAlO_2$ which was then removed with wet acid etching. The MQWs were deposited simultaneously on the two substrate types using low-pressure metalorganic chemical vapor deposition. The MQWs on C-plane sapphire exhibited a strong excitation intensity-induced PL spectrum line blue shift (up to 140 meV). However identical MQW structures on M-plane substrates showed no PL peak shift indicating an absence of polarization fields. At an excitation power density of ~50 kW/cm^2 the PL spectra peak positions for both the C- and the M-plane MQWs become nearly identical and do not change with subsequent increase of pumping. Using a triangular shaped potential well model for the spontaneous and piezoelectric built-in fields and our PL results, we confirm that such fields in the C-plane structures are much stronger and reach approximately 1.2 MV/cm. For this case, the excitation-induced PL line blue shift arises from a screening of the built-in electric field (by photo-excited carriers). Our estimations show such a field to be completely screened when the carrier density exceeds ~2×10^{19} cm^{-3}. This is consistent with the photo-induced carrier concentration at an excitation power density of about 50 kW/cm^2. In addition, at low excitation (1 kW/cm^2) PL intensity for the C-plane MQWs is ~30 times lower than for M-plane MQWs, whereas at >50kW/cm2 in both cases PL intensities become very close. It is caused by the change (due to field screening) of overlap of wave functions for carriers localized at interfaces of heterojunctions. Growth details and characterization results will be presented to further illustrate the role of polarization fields in controlling the MQW band-to-band emissions.

2:30 PM L5.4
CATHODOLUMINESCENCE OF MBE-GROWN CUBIC AlGaN/GaN MULTI QUANTUM WELLS ON GaAs (001) SUBSTRATE. D.J. As, S. Potthast, U. Köhler, A. Khartchenko and K. Lischka, Universität Paderborn, FB-6 Physik, Paderborn, GERMANY.

The commonly used hexagonal $Al_xGa_{1-x}N$/GaN heterostructures show an inherently strong spontaneous polarisation oriented along the hexagonal c-axis as well as strain induced piezoelectric polarization. Such polarization induced electric fields have a detrimental effect on the electrical and optical characteristics of GaN-based QW devices with wurtzite lattice configuration and increases the threshold current and redshifts the emission wavelength in laser diodes [1]. Using the metastable cubic modifications of $Al_xGa_{1-x}N$ and GaN, such piezoelectric effects can be avoided if the samples are grown in (001) direction. Cubic phase GaN/$Al_xGa_{1-x}N$ Multi Quantum Well structures were grown using rf-plasma assisted molecular beam epitaxy (MBE) on GaAs (001) substrates. X-ray measurements showed a high phase purity of the epilayers and reveal an Aluminum incorporation of 9 % and 25 %, respectively. The QW luminescence was tuned between 3.25 eV and 3.4 eV by means of the variation of QW barrier Aluminum content and QW width. The Quantum Well structures showed well resolved, abrupt interfaces and an excellent periodicity as estimated by Transmission Electron Microscopy (TEM) and High Resolution X-ray diffraction (HRXRD). Strong luminescence from the GaN QWs and the underlying cubic $Al_xGa_{1-x}N$ bulk material was measured by Cathodoluminescence at room temperature. The spatial localization of the QW emission was unambiguous determined by depth-resolved CL measurements. This assignment of $Al_xGa_{1-x}N$ bulk and GaN luminescence was further supported by employing a simple effective-mass quantum mechanical model. The lateral variation of the QW emission as well as its temperature dependence were studied. [1] V. Fiorentini, F. Bernardini, F. Della Sala, A. Di Carlo and P. Lugli, Phys. Rev. B **60** (1999) 8849

3:15 PM L5.5
MICROSCOPIC DESCRIPTION OF RADIATIVE RECOMBINATIONS IN InGaN/GaN QUANTUM SYSTEMS. Aurelien Morel, Pierre Lefebvre, Thierry Taliercio, Bernard Gil, Groupe d'Etude des Semiconducteurs, CNRS, Universite of Montpellier, FRANCE.

We propose a model for the recombination mechanism of electron-hole pairs in InGaN/GaN quantum wells and quantum boxes, which combines the effects of internal electric fields and of carrier localization. This model, adapted from the one developed by Thomas et al. [D.G. Thomas, J.J. Hopfield and W.M. Augustyniak, Phys. Rev. 140, A 202 (1965)] for donor-acceptor pairs, accounts very well for an important experimental features that we have discovered in recent years. This feature is the scaling law exhibited by the time decay of photoluminescence: the nonexponential shape of this decay is preserved for quantum wells and quantum boxes of various sizes, thus with emission wavelengths covering the entire visible spectrum and characteristic times covering four orders of magnitude. The decay time simply depends on the electric field, whereas the shape of the decay can be reproduced by using a single parameter which accounts for the local "nanotexture" of the ternary alloy. The excellent agreement between experimental results and this model supports the idea that optical recombinations in InGaN/GaN systems do not involve localized excitons, in the usual sense, but rather separately localized electrons and holes.

3:30 PM L5.6
DIRECT EVIDENCE FOR SUPPRESSED CARRIER RELAXATION IN InGaN NANODOMAINS. I.L. Krestnikov, M. Strassburg, N.N. Ledentsov, A. Hoffmann, A. Strittmatter, D. Bimberg, Technische Universität Berlin, Institut für Festkörperphysik, Berlin, GERMANY; F. Bertram, J. Christen, Magdeburg Universität, Institut für Experimentelle Physik, Magdeburg, GERMANY.

Dense arrays of ultrasmall In-rich nanodomains were studied by nonresonant and resonant time-resolved (TR) low-temperature photoluminescence (PL). The structures with InGaN nanodomains in a GaN matrix were grown by metal-organic chemical vapor deposition on Si(111) substrates. For nonresonant excitation at high photon energies the PL decay process demonstrates a strongly nonexponential behavior with slowing of the recombination rate with time which can be fitted by two different stretched exponents. Time constants and stretched parameters have a weak dependence of the registration wavelength. With decreasing the exiting photon energy corresponding to resonant excitation, the TRPL behavior threshold-like changes. PL decay processes can be fitted now by only one stretched exponent and

the time constant has a strong dependence on the registration wavelength. Broadening of the PL spectra is absent in this case and the linewidth is defined only by the excitation laser. A weak longwavelength shoulder is observed in addition and demonstrates a fast rise time (<5 ps) and a long radiative decay time. It can be attributed to the resonant absorption due to quasi-allowed transition between the first hole excited state and a ground electron state in size-dispersed nanodomains, followed by ultrafast relaxation to the ground state. The observations are similar to those found in InAs-GaAs quantum dots (QDs) and evidence the QD origin of the PL signal for the case of resonant excitation into the QD ground state. No resonant PL peak energy shift caused by reduced piezoelectric screening at lower overall concentrations of non-equilibrium carriers was found.

3:45 PM L5.7
TIME-RESOLVED STUDIES OF CARRIER DYNAMICS IN NITRIDE SEMICONDUCTORS GROWN HOMOEPITAXIALLY BY MBE ON GaN TEMPLATES. M. Wraback, A.V. Sampath, H. Shen, G.A. Garrett, F. Semendy, and K. Aliberti, U.S. Army Research Laboratory, Sensors and Electron Devices Directorate, Adelphi, MD; T.D. Moustakas, ECE Department, Boston University, Boston, MA.

GaN and AlGaN epilayers have been grown by MBE on HVPE and MOCVD GaN templates. Photoluminescence from the GaN epilayers possesses intensity and linewidth comparable to that obtained from the high quality GaN templates. Wavelength and intensity dependent pump-probe reflectivity measurements with ~100 fs resolution have been performed on both the GaN epilayers and the templates. For example, when band edge excitation at ~365 nm is employed, the time evolution of the characteristic $-\Delta R$ onset at $t=0^+$ in GaN epilayers can be described by a two component exponential decay, with both the relative strength and time constant of the fast component becoming smaller with decreasing excitation density. As the pump intensity is lowered by one order of magnitude, the time constant τ of the fast component in GaN on HVPE (MOCVD) drops from 87 (162) ps to 58 (85) ps, while that of the slow component increases from ~1750 (2142) ps to ~2290 (4179) ps. In addition, the strength of the slow component is ~1.3 (2.9) times that of the fast component at low excitation density, thus implying that the overall carrier lifetime is much longer than that which is normally observed in heteroepitaxially grown material. These observations suggest that the fast decay component is associated with nonradiative recombination through states in the gap, which can be saturated at high carrier density (mid $10^{18}cm^{-3}$), while the slow component may be attributed to excitonic dynamics, which contribute less at high density due to inhibition of exciton formation by Coulomb screening. Viewed in this way, the epilayer grown on the MOCVD template most likely possesses fewer defects that mediate nonradiative recombination than that grown on the HVPE template, thus implying the importance of template quality for homoepitaxial growth. Similar studies of homoepitaxially grown AlGaN layers will also be presented.

4:00 PM L5.8
DEEP DONOR ACCEPTOR PAIR LUMINESCENCE IN CO-DOPED GaN. Bing Han, Joel M. Gregie, Bruce W. Wessels, Northwestern Univ, Dept of Materials Science and Engineering and Materials Research Center, Evanston, IL; Melville P. Ulmer, Northwestern Unvi, Dept of Physics and Astronomy, Evanston, IL.

Luminescent defect centers present in p-type GaN:Mg codoped with shallow donors (oxygen or silicon) have been investigated. In addition to the 2.8 eV blue photoluminescence (PL) band, typically observed in GaN:Mg, a second PL band at 2.5 eV emerges in the heavily codoped epilayers. The thermal quenching of the luminescence was studied over the temperature range of 16–350 K. A complex temperature behavior was observed. At low temperatures the blue band dominates the spectrum, whereas the 2.5 eV green band is dominant at high temperatures. The 2.5 eV band intensity shows specific temperature dependence with a maximum at 280 K and is not observable at T < 150 K. In addition, the intensity of the 2.8 eV band exhibits linear dependence on excitation density at low excitation levels, whereas a superlinear excitation dependence with an exponent of 1.4~1.7 is observed for the 2.5 eV band. To explain the thermal quenching and excitation dependence a donor-acceptor pair (DAP) model was developed for the 2.5 eV band whereby the donor is attributed to a metastable defect. The metastable donor is tentatively attributed to the nitrogen vacancy complex. The fact that the 2.5 eV band is only observed in codoped GaN:Mg is explained by the model whereby the concentration of luminescence centers depends on the Fermi level position. Our results give experimental evidence that the nitrogen vacancy donor complex is responsible for the metastable defect behavior (e.g., persistent photoconductivity and photoluminescence) often observed in Mg-doped p-type GaN.

4:15 PM L5.9
DIELECTRIC FUNCTION OF 'NARROW' BAND GAP InN. S. Shokhovets, G. Goldhahn, Ilmenau Technical Univ, Inst of Physics, Ilmenau, GERMANY; V. Cimalla, L. Spiess, G. Ecke, O. Ambacher, Ilmenau Technical Univ, Center for Micro- and Nanotechnologies, Ilmenau, GERMANY; J. Furtmueller, F. Bechstedt, Fridrich Schiller Univ, Inst of Solid State Theory and Theoretical Optics, Jena, GERMANY; H. Lu, W.J. Schaff, Cornell Univ, Dept of Electrical and Computer Engineering, Ithaca, NY.

It was accepted for a long time that the fundamental band gap of wurtzite InN is of about 2 eV. This value resulted from absorption and photoluminescence measurements on sputtered films. However, recent studies of plasma induced molecular beam epitaxy (PIMBE) grown films with lower electron concentration and higher electron mobility indicate that the band gap is considerably narrower placing it on a range of 0.7 eV to 0.9 eV. So far no reliable experimental data have been reported on the dielectric function (DF) of InN as well as those to unambiguously demonstrate characteristic features which are related to critical points of the band structure. We performed a detailed comparison of PIMBE grown and sputtered InN films by high resolution X-ray diffraction (HRXRD), Auger electron spectroscopy (AES), photothermal deflection spectroscopy (PDS) and spectroscopic ellipsometry (SE). The DF of InN determined by SE measurements on PIMBE grown samples is in good agreement with ab initio calculations and consistent with a band gap close to 1 eV. We observe also a critical point of the band structure at a photon energy of about 5 eV. In contrast, optical spectra of sputtered InN films show an absorption edge at about 2 eV and a less pronounced structure at higher photon energies. AES and XRD studies of these layers revealed a large amount of oxygen incorporated into the crystal lattices. In addition we present the DFs of InGaN alloys in the spectral region of 0.75 eV to 5.5 eV and energies of the critical points of the band structure in dependence of the In-concentration.

4:30 PM L5.10
DETERMINATION OF THE REAL AND IMAGINERY OPTICAL CONSTANTS OF AlGaN ALLOY FILMS BY SPECTROSCOPIC TRANSMITTANCE AND REFLECTANCE CORRELATED WITH PRISM-COUPLED WAVEGUIDE MODE MEASUREMENTS. Lawrence H. Robins, Albert V. Davydov, Alexander J. Shapiro, National Institute of Standards and Technology, Gaithersburg, MD; Norman A. Sanford, National Institute of Standards and Technology, Boulder, CO; Denis V. Tsvetkov, Vladimir A. Dmitriev, Technologies and Devices International Inc., Silver Spring, MD; Stacia Keller, Umesh K. Mishra, Steven P. DenBaars, University of California, Santa Barbara, CA.

Accurate values of the refractive index (n) and absorption coefficient (α) of $Al_xGa_{1-x}N$ alloy films as functions of photon energy (E) and Al mole fraction (x) are needed as input parameters for the design of photonic and electronic devices. Spectroscopic transmittance and reflectance (T/R) is a commonly used measurement method for optical constants. A drawback of the T/R method is that, while the (index)(film thickness) product is measured accurately, n cannot be determined accurately without film thickness or other additional data. We show that curve-fitting analysis of spectroscopic, normal-incidence T/R measurements, correlated with prism-coupled waveguide mode measurements, enables accurate determination of the ordinary index $n_o(E)$ and the corresponding absorption coefficient $\alpha_o(E)$ throughout a large energy range. $Al_xGa_{1-x}N$ films with x=0 to x=0.666 grown by either MOCVD or HVPE techniques were examined by these methods. The Al mole fraction of the films was determined by energy-dispersive X-ray spectroscopy analysis. Key results are as follows. A two-Sellmeier-term function provides a good description of the energy dependence of $n_o(E)$ in each film for $E_i E_G$ (where E_G is the band gap energy). The variation of n_o with both E and x was examined by plotting $n_o(fE_G(x))$ as a function of x for several values of the parameter $f<1$ (where $fE_G(x)$ is a fixed fraction of the band gap). The function $n_o(fE_G(x))$ was found to decrease monotonically with increasing x at low energy ($f \ll 1$), and to show a non-monotonic x dependence with a minimum near $x=0.3$ at high energy ($f \approx 1$). The function used to fit $\alpha_o(E)$ has three analytic regions: (1) a bi-exponential function at energies below and near E_G; (2) a power-law function of $(E-E_G)$ slightly above E_G; (3) a linear function further above E_G. The x dependence of E_G is quadratic, with a bowing parameter equal to -1.43±0.22 eV.

4:45 PM L5.11
AlN EPILAYERS WITH HIGH OPTICAL QUALITIES – EPITAXIAL GROWTH, PROPERTIES OF BAND-EDGE EMISSIONS, AND APPLICATIONS. J. Li, K.B. Nam, M.L. Nakrmi, J.Y. Lin, and H.X. Jiang, Department of Physics, Kansas State University, Manhattan, KS.

Knowledge concerning the optical properties of AlN is very scarce, despite its importance for fundamental understanding of wide band gap semiconductor properties as well as for device applications. Previously no band-edge photoluminescence (PL) was observed in

AlN due to the lack of high quality materials as well as various challenges involved in deep UV PL measurements. We report here the MOCVD epitaxial growth and deep UV time-resolved PL studies of AlN epilayers. High quality AlN epilayers have been successfully grown on sapphire substrates. PL emission lines associated with excitonic transitions at about 6.0 eV with high quantum efficiency and narrow linewidths have been observed both at low (10 K) and room temperatures. We have demonstrated that the optical quality, quantum efficiency, and surface morphology of the high quality AlN epilayers are as good as GaN and that the thermal quenching of PL emission intensity is greatly reduced in AlN over GaN, which suggests that the detrimental effects of non-radiative recombination channels in AlN is much less severe than in GaN. The carrier dynamics of the band-edge transitions in AlN have also been studied. Important parameters including exciton binding energies and decay lifetimes have been measured. The band structure near the fundamental absorption edge has been obtained and compared with that of GaN. The availability of high quality AlN extends many existing applications of III-nitrides. With its large direct bandgap, high thermal conductivity and hardness, and high resistance to chemicals, AlN has many attractive properties and important applications in areas such as UV emitters for biological and chemical agents detection and general lighting and electronic devices operating under high power/high temperature conditions.

SESSION L6: POSTER SESSION
Tuesday Evening, December 3, 2002
8:00 PM
Exhibition Hall D (Hynes)

L6.1
In AS A SURFACTANT FOR THE GROWTH OF AlGaN/GaN HETEROSTRUCTURES BY PLASMA ASSISTED MBE.
Eva Monroy, Bruno Daudin, Noelle Gogneau, Edith Bellet-Amalric, Fabrice Enjalbert, Le Si Dang, Denis Jalabert, Julien Brault, CEA-Grenoble, Equipe mixte CEA-CNRS-UJF Nanostructures et Semiconducteurs, FRANCE.

The structural quality of $Al_xGa_{1-x}N$ alloys is often one of the limitations for the performance of nitride-based devices. The use of a surfactant appears as an attractive possibility to improve the material quality. It is known that an extra In flux impedes GaN roughening under slightly N-rich conditions, although the adequate range of In fluxes has not been established, and the effect of In on AlGaN growth has not been analyzed. In this work, we report the assessment of In as a surfactant for the growth of AlGaN/GaN heterostructures by plasma-assisted MBE.
The In stability on the growing GaN surface is analyzed as a function of the impinging In flux, concluding that there are two regimes in which an In film is dynamically-stable on GaN. These two "stability windows", corresponding to an In coverage of 1 monolayer (ML) and 2 ML, have been delimited as a function of the substrate temperature. On AlGaN surface, the presence of Al modifies the growth kinetics. As a result, the 2 ML regime is no longer stable on AlGaN ($x \geq 0.10$), and the 1 ML window becomes narrower for higher Al mole fractions. Thus, for increasing Al contents, it becomes more critical to select the In flux that guarantees surfactant effect along the whole heterostructure growth process.
AlGaN ($0 \leq x \leq 0.7$) epilayers and heterostructures were grown at 680°C, under slightly N-rich conditions, and with an In flux of 0.08 ML/s, corresponding to a stable In coverage of 1 ML. Rutherford backscattering spectrometry revealed that *no* In was incorporated. Samples present mirror-like surfaces, without metal droplets or macroscopic defects. The quality of the layers is assessed by AFM, photoluminescence and high-resolution X-ray diffraction, both in symmetric and asymmetric reflections. These results demonstrate the capability of indium as a surfactant for optimal growth of AlGaN heterostructures at low temperature by PAMBE.

L6.2
MOLECULAR BEAM EPITAXIAL GROWTH OF AlN/GaN MULTIPLE QUANTUM WELLS.
Hong Wu, William J. Schaff, Cornell University, School of Electrical and Computer Engineering, Ithaca, NY; Madalina Furis, A.N. Cartwright, State University of New York at Buffalo, Department of Electrical Engineering, Buffalo, NY; Walter Henderson, W. Alan Doolittle, Georgia Institute of Technology, School of Electrical and Computer Engineering, Atlanta, GA; A.V. Osinsky, Corning Inc., Science and Technology, Corning, NY.

AlN/GaN multiple quantum wells (MQWs) were grown on sapphire substrates by plasma-assisted molecular beam epitaxy. Growth temperature, III/V ratio, growth rate, and other growth parameters were optimized for the buffer layer and the MQWs, separately. The growth of AlN buffer was kept as Al-rich as possible while the formation of Al droplets was avoided. A GaN buffer layer was also tried but proved to be inferior to AlN buffer probably due to its larger surface roughness, higher dislocation density, and larger lattice mismatch with the AlN barrier layers in the MQWs. Very flat surfaces with a RMS roughness of 0.7nm were observed by atomic force microscopy (AFM) on the samples with both AlN buffer layer and 20 MQWs deposited under the optimized growth conditions. Abrupt interfaces and excellent periodicities of the MQWs were confirmed by X-ray diffraction (XRD) and reflectivity measurements with MQWs' satellite peaks clearly visible up to the 10th order. Room-temperature intense ultraviolet (UV) photoluminescence (PL) emission with wavelength in the range of 320-350nm was also observed from the MQWs with well width ranging from 1.0 to 1.5nm. These MQW structures can potentially be used for UV light emitters and quantum cascade lasers.

L6.3
EVOLUTION OF SUBGRAIN BOUNDARIES IN HETEROEPITAXIAL GaN/AlN/6H-SiC GROWN BY METALORGANIC CHEMICAL VAPOR DEPOSITION.
B.J. Skromme, H.X. Liu, M.K. Mikhov, G.N. Ali, and K.C. Palle, Dept of Electrical Engineering and Center for Solid State Electronics Research, Arizona State Univ, Tempe, AZ; Z. Reitmeyer and R.F. Davis, Dept of Materials Science and Engineering, North Carolina State University, Raleigh, NC.

Heteroepitaxial growth of GaN on SiC substrates offers advantages over the more common growth on sapphire, due to the electrical conductivity, smaller lattice mismatch, and higher thermal conductivity of SiC over sapphire. The effect of structural properties on luminescence has not been widely studied for GaN/SiC, however. We report characterization of the surface morphology and luminescence properties of GaN/AlN/SiC layers of various thicknesses using secondary electron imaging (SEI), panchromatic room temperature cathodoluminescence (CL), atomic force microscopy (AFM), optical Nomarski microscopy, and room and low temperature photoluminescence (PL) and reflectance. The nominally undoped GaN layers were grown by MOCVD at 1015°C on 100 nm thick AlN buffer layers (grown at 1115°C) on commercial 6H-SiC(0001) substrates. GaN layer thicknesses were 0.5, 1.0, 1.6, and 2.6 μm. A second 1.0 μm thick layer was grown by identical procedures on a piece of 6H-SiC substrate that was first etched in H_2 for 20 min. at 1600°C to remove mechanical polishing scratches and damage. Biaxial compressive lattice mismatch stress was found in all layers and decreased with increasing layer thickness, while PL linewidths decreased. The 1 μm layer on the H-etched substrate was as relaxed as the 2.6 μm layer on an unetched substrate, however. Strong variations in the strength of the yellow (2.2 eV) and band-edge emissions were observed as a function of thickness. Pronounced surface structures apparently corresponding to columnar subgrain boundaries were observed on the samples on unetched SiC. Their typical sizes increased from about 3 to 10 μm as the layer thickness increased. They were absent in the H-etched sample. These structures were generally dark (nonradiative) in the CL images, although mottled contrast is also observed inside them. Si-doped layers did not show these features, suggesting a different microstructure.

L6.4
VERTICAL COMPOSITION MODULATIONS IN AlGaN EPITAXIAL LAYERS.
A.N. Westmeyer, S. Mahajan, Dept. of Chemical and Materials Engineering, Arizona State University, Tempe, AZ; D.D. Koleske, A.A. Allerman, R.M. Biefeld, Sandia National Laboratories, Albuquerque, NM.

Epitaxial layers of AlGaN were investigated by transmission electron microscopy to understand the occurrence of compositional variations in the AlN-GaN system. AlGaN epitaxial layers of different compositions, 200 nm thick, were deposited by metalorganic chemical vapor deposition on 2 μm GaN buffer layers on (0001) sapphire substrates. The average composition x was determined by both X-ray diffraction and Rutherford backscattering spectroscopy. Analysis of plan-view electron diffraction patterns suggests that the composition is laterally homogeneous. However, cross-sectional electron diffraction patterns reveal streaking in the [0001]* direction. Cross-sectional images contain a speckle contrast characteristic of spinodal decomposition. These observations are consistent with the existence of vertical composition modulations without a clearly defined period or amplitude of compositional variation. Measurements from diffraction patterns indicate a predominant wavelength of $\lambda = 1.1 \pm 0.7$ nm for the sample with $x = 0.18$, $\lambda = 1.4 \pm 0.4$ nm for $x = 0.40$, and $\lambda = 1.7 \pm 0.7$ nm for $x = 0.75$. Arguments are developed to rationalize these observations.

L6.5
SEGREGATION EFFECTS AND BANDGAP ENGINEERING IN InGaN QUANTUM WELL HETEROSTRUCTURES.
Sergey Karpov, Roman Talalaev, Igor Evstratov, Kirill Bulashevich, Soft-Impact Ltd., St.-Petersburg, RUSSIA; Yuri Makarov, STR Inc., Richmond, VA.

Indium segregation and composition inhomogeneities in InGaN/GaN heterostructures and muliple quantum wells (MQWs) are the well-known problems repeatedly discussed in group-III nitride community. Numerous experimental observations show that microstructure of InGaN quantum wells differs significantly from the expected one. Although homogeneous InGaN/GaN MQWs with low indium contents can be grown by optimizing growth conditions, the control of interface abruptness and indium distribution within the quantum wells still remains a problem, especially for layer with high indium content. In this paper a theoretical analysis of MOVPE grown GaN/InGaN/(Al)GaN single and multiple quantum wells is performed. Effect of operating conditions such as growth temperature, reactor pressure and growth rate on indium incorporation and composition profile in single and multiple quantum wells is studied. Model predictions are compared to available experimental data and possible ways to achieve controlled indium distribution are discussed. The composition profile in a GaN/InGaN/(Al)GaN QW is found to be poorly sensitive to such MOVPE parameters as pressure and growth rate. The results suggest that specific procedures like indium pre-deposition and growth interruption may strongly affect the composition profile of an InGaN QWs. Segregation effect on the optical properties of typical LED quantum well device structures was analyzed using quantum mechanics computations.

L6.6
INDIUM DISTRIBUTION INSIDE QUANTUM WELLS: THE EFFECT OF GROWTH INTERRUPTION IN MBE AND MOCVD. A.M. Sanchez, P. Ruterana, ESCTM-CRISMAT, UMR6508-CNRS, ISMRA, Caen, FRANCE; S. Kret, Institute of Physics, PAS, Warsaw, POLAND; P. Dluzewski, G. Jurczak, CMSG IFTR PAS, Warsaw, POLAND; N. Grandjean, B. Damilano, P. De Mierry, J. Massies, Z. Bougrioua, P. Gibart, CRHEA, UPR 10 CNRS, Valbonne, FRANCE.

The III-N semiconductor materials technology is progressing rapidly with many practical applications. InGaN/GaN quantum wells constitute the active structure in light emitting diode and laser diodes performed on this materials. It has been reported the observation of InGaN quantum-dot like associated with indium rich regions in the well region [1]. Recently, a nearly constant indium compositions in InGaN wells has been determined in samples with growth interruption by metalorganic chemical vapour deposition (MOCVD) whereas indium composition fluctuations are observed for no growth interruptions [2]. The outstanding differences in the growth parameters utilized in MOCVD and molecular beam epitaxy (MBE) affect considerably the structural quality of the heterostructures. In this work we analyze the indium composition fluctuations InGaN/GaN quantum wells in samples grown by MOCVD and MBE. In both series of samples the growth interruption effect on the indium fluctuation is determined. Detailed analysis of High Resolution Transmission Electron Microscopy (HRTEM) images obtained from cross sectional specimen supply the measurements of the strain in this system due to the lattice mismatch between both materials. The indium concentration calculation is carried out from the measured distortion in these samples. In order to solve the main limitations of the quantitative HRTEM, i.e. strain relaxation and projection, we applied finite element methods. [1] Y. Narukawa, Y. Kawakami, M. Funato, S. Fujita and S. Nakamura, Appl. Phys. Lett. 70 (1997) 981 [2] H.K. Cho, J.Y. Lee, N. Sharma, C.J. Humpreys, G.M. Yang, C.S. Kim, J.H. Song and P.W. Yu, Appl. Phys. Lett. 79 (2001) 2594

L6.7
DEPTH PROFILING InGaN/GaN MULTIPLE QUANTUM WELLS BY RUTHERFORD BACKSCATTERING: THE ROLE OF In/Ga INTERMIXING. S. Pereira and E. Pereira, Departamento de Fisica, Universidade de Aveiro, PORTUGAL; E. Alves and N.P. Barradas, Instituto Tecnologico e Nuclear, Sacavem, PORTUGAL; K.P. O'Donnell, Department of Physics, University of Strathclyde, Glasgow, UNITED KINGDOM; C. Liu, C.J. Deatcher, I.M. Watson, Institute of Photonics, University of Strathclyde, Glasgow, UNITED KINGDOM.

We report a detailed compositional analysis of In(x)Ga(1-x)N/GaN multiple quantum wells (MQWs) grown by metal-organic chemical vapour deposition. Depth profiles of the InN fraction, x, in the MQWs were determined by grazing incidence Rutherford backscattering spectrometry (RBS). Careful simulation of the RBS spectra provides precise estimations of individual well compositions, thickness and the extent of In/Ga intermixing. It is ascertained that intermixing, and In segregation to the GaN cap layer, increase strongly with the value of x in the wells and with the number of periods in the MQW stack. Additionally, the deleterious effects of interdiffusion on the emission properties of MQWs are revealed by comparing the luminescence properties of samples with the same x but with a different number of periods, which show a different degree of In/Ga intermixing. Detailed surface analyses by atomic force and electron microscopy further reveal that MQWs with a larger extent of intermixing also have an increased density, lateral size and depth of V-pit defects. These findings suggest that dislocations and pitting, resulting from the increased misfit energy (via increasing x or number of wells), are the main mechanism of the intermixing process.

L6.8
LATTICE VIBRATIONS STUDIES OF WURTZITE $In_xGa_{1-x}N$ FILMS BY COMBINING STRUCTURAL AND OPTICAL CHARACTERIZATION TECHNIQUES. M.R. Correia, S. Pereira, E. Pereira, Universidade de Aveiro, Dept. Física, Aveiro, PORTUGAL; A. Kasic, M. Schubert, University of Leipzig, Institute for Experimental Physics II, Leipzig, GERMANY; J. Frandon, M.A. Renucci, Laboratoire de Physique des Solides, CNRS-UMR 5477, UniversitéPaul Sabatier, Toulouse, FRANCE; E. Alves, D. Sequeira and N. Franco, Instituto Tecnológico e Nuclear, Dep. Física , Sacavém, PORTUGAL.

We report a detailed study on optical phonons in hexagonal $In_xGa_{1-x}N$ films for $0.06 \leq x \leq 0.24$ combining structural and optical characterization techniques. Some of the InGaN layers, which were grown by MOCVD on GaN/sapphire templates, exhibit strain and/or composition inhomogeneities along the growth direction [1]. In the Raman spectra, recorded in backscattering geometry at room temperature, for an excitation energy of 3.0 eV, only the $A_1(LO)$ phonon mode of InGaN is detected due to strong resonance effects. The $A_1(LO)$ phonon mode shifts to lower frequencies with increasing In content, but the amount of this shift is smaller than that we expect for relaxed material. This observation is discussed considering previous structural film characterization carried out by Rutherford backscattering spectrometry and X-ray diffraction studies. The results show that the $A_1(LO)$ phonon mode frequencies observed under the chosen excitation conditions are related to the more strained region near the interface InGaN/GaN. In order to overcome the difficulty in detecting further InGaN phonon modes by Raman scattering, we employ infrared spectroscopic ellipsometry (IRSE), a novel method for the IR optical characterization of group-III nitride thin-film heterostructures. Upon precise IRSE model line shape analyses, effects of strain and composition on the $E_1(TO)$ phonon mode frequency can be quantified. While the $A_1(LO)$ phonon mode of InGaN is clearly detected for films thicker than 0.5μm, the $E_1(TO)$ mode resonance can be observed even for rather small film thickness values (d$\sim$100 nm). The IRSE results obtained for ternary layers, which exhibit strong strain and/or composition inhomogeneities, agree very well with results from structural studies. The composition dependence on the $E_1(TO)$ phonon mode frequency for fully relaxed material can be derived. According to our results, the $E_1(TO)$ phonon displays a one-mode behaviour for $0.06 \leq x \leq 0.24$. [1] S. Pereira, M.R. Correia, E. Pereira, K.P. O'Donnell, E. Alves, A.D. Sequeira and I.M. Watson and C.J. Deatcher, Appl. Phys. Lett. 80, (2002) 3913.

L6.9
NEARLY-ZERO FIELD QUATERNARY InAlGaN/GaN QUANTUM WELLS GROWN BY RF-MBE. N.T. Pelekanos, M. Androulidaki, E. Dimakis, F. Kalaïtzakis, E. Aperathitis, K. Tsagaraki, A. Georgakilas, FORTH, Heraklion, GREECE; E. Bellet-Amalric, D. Jalabert, CEA, Grenoble, FRANCE.

Quaternary nitride alloys are an important heterostructure engineering tool, not only because they allow to vary independently the energy gap and the lattice parameter, but also in view of the possibility to achieve polarization-matched nitride heterostructures which will be free of internal electric fields. All samples in this report were fabricated by rf plasma-assisted molecular beam epitaxy. We studied first a series of $In_xAl_{0.4}Ga_{0.6-x}N$ thin films where the In-content ranged from 0 to 15%. The alloy concentrations were determined by XRD and RBS. Strong PL emission was observed up to 300K for all x. Depending on x, the PL peak position varied from 290nm to 435nm. The comparison of the PL with reflectivity and transmission spectra revealed that the PL corresponds to band-edge emission. The In-bandgap bowing parameter needed to reproduce the observed x-dependence of the gap was found b$\approx$8eV, which is double the value of InGaN alloys. Next, we investigated a series of $GaN/In_xAl_{0.4}Ga_{0.6-x}N$ multiple quantum well (MQW) samples with varying x from 0 to 10% and different barrier and well widths. Detailed experiments performed on $In_{0.10}Al_{0.35}Ga_{0.55}N$/GaN QWs, where the quaternary is the QW layer due to the large bowing, have clearly shown that these QWs are nearly free of polarization field. To be precise, the measured field was found 0.2MV/cm, i.e. one order of magnitude smaller than equivalent $GaN/Al_yGa_{1-y}N$ QWs with the same bandgap difference between barrier and well layers. We have grown optimised InAlGaN/GaN laser structures with nearly zero field in the active QWs, as well as reference GaN/AlGaN ones. Mirrors were reactive-ion etched. In preliminary optical pumping experiments, we achieved room temperature lasing from both quaternary and reference structures. The optical power threshold for the quaternary laser was found distinctly lower than the reference, in agreement with the strongly reduced internal field.

L6.10
SINGLE-PHASE EPITAXIAL WURTZITE $Al_{1-x}In_xN$ ($0.35<x<0.52$) THIN FILMS. Timo Seppänen, Sukkaneste Tungasmita, György Radnoóczi, Lars Hultman, Jens Birch, Linköping University, Dept of Physics and Measurement Technology, Linköping, SWEDEN.

$Al_{1-x}In_xN$ is a relatively new ternary III-V nitride semiconductor alloy with many desirable properties. $Al_{0.87}In_{0.17}N$ would be perfectly lattice matched with GaN, and the wide band gap difference; 6,2 eV (AlN) to 1,9 eV (InN) between the two binaries would provide a high confinement barrier for charge carriers. It also makes it possible to engineer an alloy with emission anywhere in-between the far ultra-violet and near infrared spectral region. However, $Al_{1-x}In_xN$ has a miscibility gap in the $0.1<x<0.9$ region. Only a few successful attempts to grow this meta-stable phase have been made by techniques such as metal-organic vapor phase epitaxy (MOVPE) and plasma-source molecular beam epitaxy (PSMBE). This work presents epitaxial wurtzite single-crystal $Al_{1-x}In_xN$ films with compositions in the miscibility gap grown by reactive dual DC magnetron sputtering. The alloys were deposited in a UHV chamber onto MgO(111) substrates with a 70 nm epitaxial ZrN(111) buffer layer at temperatures between 300 and 900 °C. High resolution XRD showed that (0001)-oriented wurtzite $Al_{1-x}In_xN$ was formed. The composition was estimated from Vegards law using the c-axis lattice spacing to range from x=0.35 to 0.52 at growth temperatures up to 600 °C. At 900 °C almost pure AlN with domain sizes in the order of 100 nm, as seen by cross-sectional TEM, was formed. The film structure was for all growth conditions columnar with column base widths ranging from 10 to 100 nm. The films grown at 300 °C were found to have a lateral composition gradient within the columns. Furthermore, these alloys exhibited strong cathodoluminescence in the range ~3.43.2 eV (at 4 K), depending on x. These results show that it is possible to grow $Al_{1-x}In_xN$ with x=0.35-0.52 and a band-gap of at least 3.2 eV by sputter deposition, without experiencing spinodal phase separation, at temperatures below 600 °C.

L6.11
THERMOELECTRIC PROPERTIES OF AlInN AND AlGaInN GROWN BY REACTIVE RF-SPUTTERING: TARGETTING A THERMOPOWER DEVICE. Shigeo Yamaguchi[a,b], Yasuo Iwamura[a,b], Atsushi Yamamoto[b]; [a]Kanagawa University, Dept. of Electrical, Electronic and Information Engineering,Yokohama, JAPAN; [b]National Institute of Advanced Industrial Science and Technology, Energy Electronics Institute, Tsukuba, JAPAN.

Optical devices such as light-emitting devices using GaN-based nitrides have already been commercialized, and nitrides have currently been intensively studied in the search for other applications, e.g., high electron mobility devices and power devices. We have more recently studied the thermoelectric properties of ternary AlInN and quaternary AlGaInN systems to open out a new device field using III-nitrides, the field of thermoelectricity. AlInN and AlGaInN systems are well known to be important materials for optical and electronic devices because of its large bandgap and controllability of it by altering the content of the elements. We have recently demonstrated a potential for another device application, a thermopower device using III-nitrides. Among III-nitrides, for AlInN and AlGaInN with high In content, their properties are almost unknown and are difficult to grow, and thus they have been less studied than other III-nitride alloys. Samples studied here were AlInN and AlGaInN, with high In content (>0.4). They were prepared by the reactive RF sputtering method. AlInN and AlGaInN were grown on SiO_2 glass substrates at 100 °C with a mixture of N_2 and Ar gases. The thicknesses of the samples were 0.3-1.0 μm. X-ray diffraction analysis of $2\theta/\omega$ scan showed that all samples were of wurtzite type. In addition, electrical resistivity and Seebeck coefficient were measured by the dc method with a temperature gradient of 4K in the temperature range of 100-700 °C. All samples assessed here showed n-type conductivity of the order of 10^{17}-10^{18} cm^{-3}. For AlInN and AlGaInN, with increasing In content, the resistivity decreased. For all samples, with increasing temperature, the resistivity decreased, indicating the semiconductor behavior. We obtained a power factor of $1.0\times10^{-4}W/mK^2$ at 700 °C for AlInN, strongly suggesting that AlInN is a good candidate for a thermoelectric material.

L6.12
X-RAY DIFFRACTION ANALYSIS OF GaN, AlN, AlGaN AND InGaAlN. H. Kang, Z.C. Feng, and Ian Ferguson, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA; S.P. Guo, M. Pophristic, and B. Peres, EMCORE Corporation, Somerset, NJ.

The quality of optoelectronic and electronic devices in the III-Nitrides depends critically on the defect density of the epitaxial layers and the quality of the interface between the layers. X-Ray Diffraction (XRD) can rapidly provide information about the structural properties of individual layers and device structures for the rapid optimization of growth conditions. In XRD measurements, the FWHM measurement of rocking curve can be used to estimate tilt and twist angles from which the densities of screw and edge type defects can be estimated. Most III-Nitrides with large defect densities (10^6 cm^{-2} up to 10^{11} cm^{-2}) exhibit a mosaic structure which can be characterized by some average coherence length which can also be estimated from the x-ray data. The tilt angle and coherence length parallel to the surface can be derived by a simple graphical method, a Williamson-Hall plot; a linearly fitted line of the x-ray FWHMs of the symmetric (00L) reflections, L = 2, 4 or 6. The slope of the linearly fitted line provides the tilt angle and the coherence length that can be estimated by the y-intersection. In this work, this technique was extended from simple binary materials such as GaN and AlN to consider intermediate $Al_xGa_{1-x}N$ compositions. A series of high quality GaN, AlN, $Al_xGa_{1-x}N$ and $In_yAl_{1-x}Ga_{1-x-y}N$ samples were grown by MOCVD and the x-ray study was completed using a Philips XPert MRD system. X-ray linewidths of <150 arcsec were obtained indicating the high quality of the epitaxial growth. A study of the systematic variation of coherence length with $Al_xGa_{1-x}N$ alloy composition was studied. A comparison was made with $In_yAl_{1-x}Ga_{1-x-y}N$ materials, with a similar $Al_xGa_{1-x}N$ composition, to investigate the effects of indium incorporation on the structural properties of the alloy.

L6.13
RARE EARTH DOPED GaN LUMINESCENT FILMS GROWN BY MOCVD. M. Pan, A.J. Steckl, University of Cincinnati, Dept of ECECS, Nanoelectronics Laboratory, Cincinnati, OH.

Rare earth doped gallium nitride films have been grown successfully by metalorganic chemical vapor deposition (MOCVD) technique. Different materials, such as glass, Si and sapphire, have been employed as substrates. Trimethylgallium and ammonia were used for gallium source and nitrogen source, respectively. For rare earth doping, novel precursors of rare earth beta-diketonates were used and the MOCVD system was modified specifically to match temperature requirement of the dopant line. X-ray diffraction (XRD) spectra have shown that the obtained doped GaN films have an oriented growth at < 0001 > direction of hexagonal crystal structure. Scanning electron microscope (SEM) photos indicate that the films have a columnar structure. The surface roughness of the films was measured with atomic force microscope (AFM). The concentration of doped rare earth elements was analyzed by using secondary-ion mass spectrometry (SIMS) and Rutherford backscattering. Carrier gas flow rate and the temperature of the RE source have a strong effect on the rare earth concentration in the GaN films. Incorporation of rare earth elements into the GaN films versus growth temperature and growth pressure has also been investigated. We have fabricated both alternating current electroluminescent device (ACELD) and direct current electroluminescent device (DCELD) based on the MOCVD grown rare earth doped GaN films. Red and green emission have been observed at room temperature.

L6.14
PHOTOPUMP-ENHANCED EMISSION IN RARE-EARTH-DOPED GaN ELECTROLUMINESCENT DEVICES. D.S. Lee, A.J. Steckl, University of Cincinnati, Nanoelectronics Laboratory, Cincinnati, OH.

Rare-earth-doped GaN (GaN:RE) electroluminescent devices (ELDs) have been shown[1] to be important for multi-color applications, such as flat panel displays (FPDs). Multiple color emission has been demonstrated[2] by laterally integrated DC-driven ELDs using both a liftoff process and a shadow mask technique. RGB colors have also been successfully obtained[3] from AC-driven GaN:RE ELDs on glass substrates. It is very important to produce high ELD brightness and efficiency in the visible emission. In particular, bright blue emission still remains a major challenge for most ELDs. In this paper we report a significant enhancement in visible electroluminescence (EL) brightness by photopumping operational ELDs with UV light. EL emission is considerably increased by UV photopumping ELDs fabricated on GaN:RE grown on (111) Si. With radiation from a HeCd laser (325nm), both blue (from GaN:Tm) and green (from GaN:Er) EL brightness have been enhanced up to 2 orders of magnitude depending on bias conditions. We explain the basic mechanism as follows: photo-generated electrons produced by above-bandgap excitation are added to electrically injected electrons and both types of electrons contribute to EL emission through impact excitation. The EL intensity increases monotonically with increasing applied bias and photopumping power. EL intensity gain by photopumping over the no pumping case is more efficient at relatively low bias levels. This visible EL enhancement can be applied to FPDs not only for enhanced brightness, especially blue, but also for improved color balance. Photopumping also has potential applications as UV indicators and detectors. [1]A. J. Steckl J. Heikenfeld, D. S. Lee and M. garter, Mater. Sci. Eng. B81, 97 (2001). [2]D. S. Lee and A. J.

Steckl, Appl. Phys. Lett. 80 (11), 1888 (2002). [3]J. Heikenfeld, A. J. Steckl, IEEE T. Electron. Dev., 557 (2002).

L6.15
ELECTRON MICROPROBE AND PHOTOLUMINESCENCE ANALYSIS OF EUROPIUM-DOPED GALLIUM NITRIDE LIGHT EMITTERS. R.W. Martin, S. Dalmasso, K.P. O'Donnell, Department of Physics, Strathclyde University, Glasgow, UNITED KINGDOM; A. Yoshida, Toyohashi University of Technology, Tenpaku, Toyohashi, JAPAN; the RENiBEl Network.

Rare-earth doped GaN structures offer potential for optical devices emitting in the visible region [1,2]. We describe a study of MOVPE grown GaN-on-sapphire epilayers implanted with Europium ions, producing characteristic red emission lines between 600 and 680 nm due to intra-4f(n) shell transitions. As-implanted and subsequently annealed samples are investigated using a combination of wavelength dispersive X-ray analysis (WDX), electron microscopy, cathodoluminescence (CL) and photoluminescence (PL). WDX is shown to be a powerful technique for quantifying rare-earth concentrations in GaN, with varying electron beam voltages allowing a degree of depth profiling, further enhanced by the simultaneous collection of room temperature luminescence (CL) from the analysed region [3]. The intensities of the sharp lines observed in the luminescence spectrum are compared to the doping density (between 10^{14} and 10^{15} cm^{-2}) and the Eu content measured by WDX, using a Eu-doped glass standard. Differences observed in the luminescence spectra produced by laser and electron beam excitation will be discussed along with the importance of the annealing conditions, which "heal" defects visible in the electron micrographs. 1. A.J. Steckl, J. Heikenfeld, D.S. Lee and M.J. Garter, Mater. Sci. Eng. B 81 97 (2001) 2. E. Alves, K. Lorenz, R. Vianden, C. Boemare, M.J. Soares, T. Monteiro, Mod. Phys. Lett. B 15 1281 (2001) 3. R.W. Martin, P.R. Edwards, K.P. O'Donnell, E.G. Mackay, and I.M. Watson, phys. stat. sol. (a) 192 (2002) in press

L6.16
LATTICE LOCATION AND CATHODOLUMINESCENCE STUDIES OF YTTERBIUM/THULIUM DOPED ALUMINIUM NITRIDE. Ulrich Vetter, Jan Zenneck, Carsten Ronning, Hans Hofsäss, 2. Physikalisches Institut, Universität Göttingen, Göttingen, GERMANY; Marc Dietrich, ISOLDE Collaboration, CERN, Geneva, SWITZERLAND.

The implementation of light-emitting devices from IR to UV, based on luminescence of intra-4f transitions of lanthanides, is up to now a challenging task. The intensity of these transitions is strongly dependent on the symmetry of the ions site in the host as well as the properties of the host itself. Strong intra-4f luminescence can be observed even at room temperature for Eu and Tb doped into AlN by ion implantation [1]. Up to now the lattice sites of lanthanides in AlN were not yet determined. In order to perform direct lattice location studies of lanthanide impurities in AlN, radioactive ^{169}Yb ions ($T_{1/2}$=32.0 d) were implanted at the on-line isotope separator ISOLDE at CERN into single crystalline 2H-AlN layers grown on 6H-SiC.Lattice location studies were performed by means of the emission channeling technique yielding substitutional Al sites for Yb ions. The annealing behaviour of the implanted samples was studied in a temperature range 293 K - 1293 K. Cathodoluminescence investigations of intra-4f transitions of Tm were performed in a temperature range 12 K 300 K on the same samples after complete decay of ^{169}Yb to ^{169}Tm. The samples show a strong luminescence in the range 460 nm 470 nm up to 300 K. Temperature dependent linewidths of transition between and energy shift of some multiplets as well as time resolved CL spectra will be presented. [1] W. M. Jadwisienczak et al., Journal of Applied Physics 89 (2001) 43844390

L6.17
MULTICOLOR INTEGRATION ON RARE-EARTH DOPED GaN ELECTROLUMINESCENT THIN FILMS. Y.Q. Wang and A.J. Steckl, Nanoelectronics Laboratory, Department of Electrical and Computer Engineering & Computer Sciences, University of Cincinnnati, Cincinnati, OH.

Recently green, blue, and red electroluminescence (EL) from rare earths (RE) in-situ doped GaN has been reported. Tm, Er and Eu elements were used as the dopants for blue, green and red emission, respectively. If the EL devices emitting these colors can be integrated on a single substrate, the integrated array could be regarded as the prototype model of future generations of large-scale flat panel displays and head-mounted displays. In this report, we employed lateral integration to realize the full color integration on rare-earth doped thin film electroluminescent GaN. Three color pixel arrays have been fabricated using spin-on-glass (SOG) films as the sacrificial layers for lift-off lithography. We selected SOG as the sacrificial layer for several reasons: it contains mainly Si dioxide and little or no organic content, it can be exposed to high growth temperatures, it can be etched off in a few seconds in an HF solution. Direct-current EL devices were fabricated using indium-tin-oxide transparent electrodes. The dimension of the GaN:RE thin film pattern is 0.3 mm wide and 0.9 mm long. The size of the ITO electrodes is 0.2 mm wide and 0.7 mm long, and the EL devices are separated from each other by 0.2 mm. The blue emission from Tm-doped GaN has a peak at 477 nm, the green emission from Er-doped GaN has two peaks at 537 and 558 nm, while the red emission from Eu-doped GaN has a peak at 621 nm. Typical applied voltage was 30 40 V. The emission from the electroluminescent devices is bright enough to be easily observed by the naked eye under ambient light conditions, with green emission from the GaN:Er pixel being the strongest. The CIE coordinates of the GaN:RE phosphors demonstrate their capability for full color displays.

L6.18
ELECTROLUMINESCENCE FROM Eu-DOPED GaN MIS STRUCTURE. W.M. Jadwisienczak, H.J. Lozykowski, School of Electrical Engineering and Computer Science, Ohio University, Athens, OH; E. Kowalczyk, Institute of Electron Technology, Warsaw, POLAND; A.E. Kowalczyk, Institute of Electronic Materials Technology, Warsaw, POLAND.

Visible electroluminescence (EL) at room temperature has been achieved from a metal-insulator-semiconductor device (MIS) made on GaN thin film doped with Eu ions. The GaN film used for this investigation was grown by metal-organic chemical vapor deposition (MOCVD) on sapphire and implanted with Eu ions. MIS devices were fabricated on GaN films using silicon dioxide layer (9.5 nm) and indium-tin-oxide (100 nm) as transparent electrode deposited by electron beam evaporation. The EL spectra show dominant red emission line at 622 nm and weaker lines at 554 nm, 594 nm and 665 nm, corresponding to the transition between $^5D_{0,1}$ and $^7F_{1,2,3}$ states in Eu^{3+}. A systematic study of EL signal was conducted in 10-300 K temperature range with an applied bias voltage changing from 10-110 V, respectively. The strongest EL signal due to $^5D_0$-$^7F_2$ transition was recorded at 300 K under forward bias.

L6.19
ANALYZING THE ELECTRICAL CHARACTERISTICS OF THE Si-DOPED InGaN/GaN SHORT-PERIOD SUPERLATTICE TUNNELING CONTACT LAYER ON THE LIGHT-EMITTING DIODES. T.C. Wen, S.J. Chang, L.W. Wu, Y.K. Su, W.C. Lai, C.H. Kuo, C.H. Chen, Institute of Microelectronics & Department of Electrical Engineering, National Cheng Kung University, TAIWAN; J.K. Sheu, Optical Science Center, National Central University, TAIWAN.

A detail analysis on the electrical characteristics of the Si-doped InGaN/GaN short-period superlattice (SPS) tunneling contact layer on the light-emitting diodes (LEDs) has been performed. The forward voltage is 3.26 V and 3.7 V at 20 mA DC current for LED with $n^+In_{0.23}Ga_{0.77}N$/GaN SPS tunneling contact layer and conventional p-type GaN top contact layer, respectively. This tunneling junction is shown to be an effective method to reduce the operation voltage compared to conventional LEDs. Furthermore, the sheet resistance and specific contact resistance of each sample were measured by the circular transmission line method (CTLM). It was found that the sheet resistance for either SPS top or p-type GaN top contact layer sample is almost identical. However, the specific contact resistance for the SPS top ($7.8e^{-3}$ $\Omega\cdot cm^2$) is higher than p-type GaN top contact layer ($1.82e^{-2}$ $\Omega\cdot cm^2$). Calculating the difference of operation voltage in 20 mA between these two samples, the higher operation voltage is resulted from the higher specific contact resistance. This results suggests low resistivity $n^+In_{0.23}Ga_{0.77}N$/GaN/GaN SPS allows the reverse-bias tunneling junction to form a low-voltage drop contact.

L6.20
THE PROPERTIES OF A P IMPLANTED GaN LIGHT-EMITTING DIODE. Junjiroh Kikawa, Seikoh Yoshida and Yoshiteru Itoh, Yokohama R&D Laboratories, The Furukawa Electric Co., Ltd., Nishi-ku, Yokohama, JAPAN.

Nitride-rich $GaN_{1-x}P_x$ is very attractive for a light-emitting diode (LED) with a wider visible wavelength due to gigantic band-gap bowing. In this paper, we report on the properties of a $GaN_{1-x}P_x$ LED. The sample structure is Si-doped GaN/ P implanted Mg-doped GaN/Mg-doped GaN on a sapphire (0001) substrate. A wafer of Mg-doped GaN was implanted with P+ at room temperature with a dose of 3 x $10^{13}cm^{-2}$ at 30 keV. The measured peak density of P in the GaN was 5 x $10^{20}cm^{-3}$ based on secondary ion mass spectroscopy. Then, Si-doped GaN was over grown on the entire surface of P implanted GaN. We fabricated the LED using a dry etching technique. The current-voltage (I-V) curve of a $GaN_{1-x}P_x$ LED was measured. In the region of forward bias, the ideality factor (n) is very large, and in the reverse-bias region the reverse current has good linearity against a bias voltage of over -30 V without breakdown.

The electroluminescence (EL) of a $GaN_{1-x}P_x$ LED was measured. The spectra of EL comprised roughly two peaks: one was a strong clear peak located at around 2.9 eV, and the other was a broad weak peak located at around 2.2 eV. Each peak of the emission band had a blue shift with increasing injection current. These properties of the I-V curve and the EL spectrum are the same to those of a $GaN_{1-x}P_x$ LED, which was grown using laser-assisted metal organic chemical deposition (LAMOCVD), as reported before. This shows that the role of P atoms as a radiative recombination center does not depend on the procedure of introducing P atoms into the GaN, such as LAMOCVD or ion implantation.

L6.21
PROPERTIES OF GaN/InGaN MQW LEDs WITH Mn IMPLANTED p-GaN CONTACT LAYERS. A.Y. Polyakov, N.B. Smirnov, A.V. Govorkov, Institute of Rare Metals, Moscow, RUSSIA; G.T. Thaler, M.E. Overberg, R. Frazier, C.R. Abernathy, J. Kim, F. Ren and S.J. Pearton, University of Florida, Gainesville, FL.

Electrical, luminescent and electroluminescent properties of GaN/InGaN MQW LEDs with Mn implanted into the top p-GaN contact layer were studied. Such LEDs are seriously considered for spintronic applications because of the high magnetic Curie temperature of the Mn implanted p-GaN. I-V characteristics of the implanted LEDs bear clear evidence of the trap-limited current flow in p-GaN, the traps having the activation energy of 0.27 eV. Admittance spectroscopy and DLTS measurements suggest the introduction of deep hole traps near 0.3 eV and 0.43 eV from the valence band edge in p-GaN. MCL spectra show the emergence of very strong yellow and blue bands. Electroluminescence spectra was not affected but the operating voltage of the implanted LEDs was much higher than in control samples without implantation (about 9V instead of about 4V). Comparison with the results obtained on Mn implanted single layers allow to attribute the blue luminescence with the formation of complexes between the Mn and some point defects, while the hole traps detected in DLTS most likely come from radiation defects diffusing from the Mn implanted region.

L6.22
EFFECT OF THICKNESS VARIATION IN HIGH-EFFICIENCY InGaN/GaN LIGHT EMITTING DIODES. J. Narayan and H. Wang, Department of Materials Science and Engineering North Carolina State University, Raleigh, NC; Jinlin Ye, Schang-Jing Hon, Kenneth Fox, Jyh Chia Chen, H.K. Choi, and John C.C. Fan, Kopin Corporation, Taunton, MA.

In Ga $1-x$)N/GaN multi-quantum-well (MQW) light emitting diodes (LEDs) having periodic thickness variation in In Ga $1-x$)N active layers exhibit substantially higher optical efficiency than LEDs with uniform In Ga $1-x$)N layers(1). In these nano-structured LEDs, the thickness variation of the active layers is found to be more important than In composition fluctuation in quantum confinement of excitons (carriers). Detailed STEM-Z contrast analysis, where image contrast is proportional to Z2 (atomic number)2, was carried out to investigate the thickness variation as well as the spatial distribution of In. In the nano-structured LEDs, there are short-range thickness variations (SR-TV, 3-4 nm period and $<$ 10 % variation) and long-range thickness variations (LR-TV, 50-100 nm period and 20-50% variation) in In Ga $1-x$)N layers. It is envisaged that LR-TV is the key to quantum confinement of the carriers and enhancing the optical efficiency. We propose that the LR-TV thickness variation is caused by two-dimensional strain in the In Ga $1-x$)N layer below its critical thickness. The SR-TV may be caused by In composition fluctuation.
(1) J. Narayan et al. Applied Physics Letters (July, 2002)

L6.23
Abstract Withdrawn.

L6.24
EFFECTS OF TRANSPARENT METAL SIZE ON OPTICAL PROPERTIES OF GALLIUM NITRIDE BASED LED. Jaehee Cho, Hye Jeong Oh, C. Sone, Y. Park, Materials and Devices Lab., Samsung Advanced Institute of Technology, Suwon, KOREA.

LED performance has been greatly improved by advanced materials growth technique, device structures, and fabrication methods. Transparent metals on p-GaN should have properties of good ohmic contact and low absorption of emission light without deteriorating current spreading. In this work, we report improved efficiency of GaN/InGaN LEDs by employing various transparent metal sizes. Effects of transparent metal size were investigated using current-voltage characteristics and optical power. This study reveal that light output power is influenced by transparent metal contact size for uv LEDs. The tendency is related to the amount of dead current which does not contributed to radiative emissions. The dead current was resulted from non-radiative recombination center such as impurities and defects in MQWs active region. Therefore there exists the optimized transparent metal contact size which gives the largest power conversion efficiency for optical power in fixed chip size. On the contrary to uv LEDs case, the dead current of blue LEDs is not varied largely by metal contact sizes, which implies that defects play a different role depending on wavelength.

L6.25
INFLUENCE OF Si-DOPING ON THE CHARACTERISTICS OF InGaN/GaN MULTIPLE QUANTUM WELL BLUE LIGHT EMITTING DIODES. J.M. Tsai, South Epitaxy Corporation, TAIWAN; T.C. Wen, S.J. Chang, L.W. Wu, Y.K. Su, W.C. Lai, C.H. Kuo, C.H. Chen, J.F. Chen, Institute of Microelectronics & Department of Electrical Engineering, National Cheng Kung University, TAIWAN; J.K. Sheu, Optical Science Center, National Central University, TAIWAN.

Although, there are several reports investigating the effects of Si doping on the properties of GaN epilayers, InGaN/GaN multiquantum well (MQW), and GaN/AlGaN MQW. There are not many studies focus on how the Si-doping in the GaN barrier layers of InGaN/GaN MQW light emitting diodes (LEDs). In this investment, a detailed study on the effects of Si-doping in the GaN barrier layers of InGaN/GaN multiquantum well MQW LEDs has been performed. From the double crystal X-ray diffraction (DCXRD) spectra, it was found that the high-order satellite peaks of the LED with unintentionally doped barrier were broad with a larger FWHM. This result indicates that Si-doping in barrier layers can improve the crystal and interfacial qualities of the InGaN/GaN MQW LEDs. Furthermore, the forward voltage is 3.5 V and 4.52 V, the 20mA luminous intensity is 36.1 mcd and 25.1 mcd for the LED with Si-doped barrier and unintentionally doped barrier, respectively. These results suggests that one can significantly improve the performance of InGaN/GaN MQW LEDs by introducing Si doping in the GaN barrier layers.

L6.26
GaN/InGaN MQW LEDs WITH THE n-GaN LAYER ON TOP GROWN BY MBE AND DOPED WITH Mn. A.Y. Polyakov, N.B. Smirnov, A.V. Govorkov, Institute of Rare Metals, Moscow, RUSSIA; G.T. Thaler, M.E. Overberg, R. Frazier, J. Kim, F. Ren and S.J. Pearton, University of Florida, Dept of Materials Science and Engineering, Gainesville, FL.

Electrical, luminescent and electroluminescent properties of GaN/InGaN MQW LEDs with the bottom p-GaN layer and the MQW region grown by MOCVD and the upper n-GaN layer doped with Mn grown by MBE were studied. Such LEDs are pursued because of the high magnetic Curie temperature of the GaMnN films grown by MBE which makes these LEDs of potential interest for spintronic applications. Admittance spectroscopy measurements on control samples without Mn showed that the series resistance of the devices is determined by the p-type region, the electroluminescence spectra consists of two peaks, the 2.4 eV and the 2.6 eV. MCL imaging of the structure shows that the QW region actually consists of domains with characteristic dimensions of several microns. The 2.6 eV luminescence comes from the bulk of the domains, 2.4 eV line comes from the boundaries. Implantation of Mn greatly increases the series resistance of the diode. It does not change the spectrum of EL but increases the operating voltage to 15V. Measurements of single GaMnN films grown by MBE show that they are characterized by rather high n-type resistivity and very low photosensitivity, the latter because of recombination via Mn acceptors.

L6.27
FABRICATION AND CHARACTERIZATION OF III-NITRIDE MICRO-SIZE UV EMITTERS. K.H. Kim, S.X. Jin, J.Y. Lin, and H.X. Jiang, Department of Physics, Kansas State University, Manhattan, KS.

We report the fabrication and characterization of UV (340 nm) micro-size light emitting diodes (LEDs) and arrays based on AlGaN/AlGaN and AlGaN/InAlGaN quantum wells. Epitaxial growth by MOCVD as well as bandgap engineering for obtaining UV emitter structures will be discussed. The fabrication processes of micro-size UV emitters will be presented. Device properties, including I-V and L-I characteristics, are compared with those of conventional UV LEDs as well as of micro-size blue emitters. It is found that the problems associated with UV emitters, such as poor current spreading and extraction efficiency, are significantly reduced in micro-size UV emitters. The micro-LED size dependencies of the output power, series resistance, and operating speed have been measured. The applications of III-nitride micro-size solid-state UV emitter arrays for chip-scale integration of Chem/Bio sensors for detection of chemical or biological agents are also discussed.

L6.28
EFFICIENT GaN-BASED MICRO-LED ARRAYS. H.W. Choi, C.W. Jeon, M.D. Dawson, Institute of Photonics, University of Strathclyde, UNITED KINGDOM; P.R. Edwards, R.W. Martin, Dept of Physics, University of Strathclyde, UNITED KINGDOM.

16x16 arrays of 20μm diameter GaN-based micro-emitters have been fabricated and characterized. Interconnection between individual emitters through a metal spreading layer has been made possible by forming non-vertical sidewalls, achieved with anisotropic ICP etching, allowing for uniform step coverage. The devices exhibit good electrical properties, with turn-on voltage and operating voltage (at 20mA) of 2.93V and 3.49V respectively. Emitting at 370nm, 1.13mW of power (at 100mA) was measured from the bare chips in a probe-station configuration.

L6.29
CHARACTERISTICS OF STRAIN INDUCED CLEAVED FACET IN InGaN LASER DIODE ON EPITAXIALLY LATERAL OVERGROWN GaN ON SAPPHIRE. Kwang- Ki Choi, S.H. Chae, J.S. Kwak, J. Cho, O.H. Nam, Materials and Devices Laboratory, Samsung Advanced Institute of Technology, Suwon, KOREA.

In InP and GaAs material systems laser facets are formed by cleaving the epitaxial layers and the substrate along a mutual cleavage plane. Since lattice mismatch between sapphire and GaN is partly accommodated by a 30 degree rotation of the GaN unit cell relative to the sapphire surface, the fabrication of cleaved facets in InGaN laser diode grown on c-plane sapphire substrate is more difficult. A variety of approaches have been published to overcome this problem including dry-etching, growing on GaN substrate that allows cleaving by conventional cleaving technique. In this study, we report on the fabrication of laser facets by strain induced cleaving (SIC) method and on the characterization of the SIC facets in InGaN laser diode. Nitride layers for the laser structure were grown on a c-plane sapphire substrate and epitaxially lateral overgrowth (ELO) GaN on c-plane sapphire using MOCVD. Ridge and MESA stripes were formed on top of the layers using chemically assisted ion beam etching (CAIBE), Ti/Al and Pd/Cr/Au were produced on n-GaN and p-GaN, respectively. To achieve steep and smooth facets by SIC, the laser diode grown wafer is thinned to 120 for making strain and design of experiment (DOE) is used for optimized conditions. Atomic force microscopy (AFM) and scanning electron microscopy (SEM) are used for evaluation of the SIC facets. We compared the characteristics of the SIC facets grown on ELO GaN and on Sapphire. AFM shows the SIC facets of ELO GaN with root-mean-square roughness of 1nm and are vertical to the ridge stripe. It also shows that the wing region is more smooth than the seed region, this result is explained by induced strain and the ELO structure. GaN layer grown on the sapphire is cleaved inducing many streaks on the facet by scribing force of sapphire substrate, but the ELO GaN region is cleaved laterally by strain. This strain originate from wafer bending which come from the large lattice mismatch between GaN layer and sapphire substrate. This rms roughness is the lowest value ever have been reported and the facets are atomically flat. This characteristics indicates that SIC solved the cleaving problem in the ELO GaN on Sapphire and is more effective method than any other approaches for making smooth facet

L6.30
GROWTH AND CHARACTERIZATION OF DEEP UV EMITTER STRUCTURES GROWN ON SINGLE CRYSTAL BULK AlN SUBSTRATES. X. Hu, R. Gaska, Sensor Electronic Technology, Inc, Latham, NY; C. Chen, J. Yang, E. Kuokstis, A. Khan, Univ of South Carolina, Dept of EE, Columbia, SC; G. Tamulaitis, I. Yilmaz, M.S. Shur, Rensselaer Polytechnic Institute, Dept of ECE and CIE, Troy, NY; C. Rojo, L. Schowalter, Crystal IS, Inc, Latham, NY.

We report on high Al-content (Al > 40%), AlGaN-based deep UV emitter structures (emission wavelengths < 300 nm) grown over single crystal, slightly off c-axis (5.8 degrees) Al-face bulk AlN substrates. AlN/AlGaN multiple quantum well (MQW) structures with up to 50% of Al in the well material were grown using low-pressure MOCVD and characterized using X-ray, AFM, SEM and photoluminescence techniques. The estimated growth defect density in the structures was in the range from $10^6/cm^2$ to $10^7/cm^2$. This is about three orders of magnitude higher that in the initial bulk AlN substrates and about three orders of magnitude lower than in our AlInGaN-based structures grown on sapphire or SiC substrates. The shortest room temperature emission wavelength close to 260 nm was measured in the structures with 50% of Al and 5 nm thick quantum wells using two light sources for selective excitation of QW (213 nm wavelength) and QW+barrier (193 nm wavelength) region. A weak temperature dependence (from 8 K to 300 K) of the luminescence intensity and the absence of a blue shift of the luminescence peak with increasing excitation intensity pointed to low density of localized states. This is in a good agreement with X-ray data, which indicated very high quality of MQW structures. We will also present the data on the deposition and testing of complete UV LED structures on bulk AlN. To date, the shortest achieved electroluminescence peak wavelength is 298 nm, which is slightly higher than in our best LEDs on sapphire (285 nm).

L6.31
DEPOSITION OF GaN FILMS ON GLASS SUBSTRATE AND ITS APPLICATION TO UV ELECTROLUMINESCENT DEVICES. T. Honda, K. Iga and H. Kawanishi, Dept. of Electronic Engineering, Kohgakuin University, JAPAN; T. Sakaguchi and F. Koyama, P&I Lab., Tokyo Institute of Technology, JAPAN.

GaN-based electroluminescent devices (ELDs) operating in UV and visible spectral regions were fabricated using GaN films deposited on glass substrates by the compound source molecular beam epitaxy (CS-MBE) technique. GaN (5N) and ammonia were used as source materials. Although GaN films were deposited using GaN powders and no additional nitrogen source, the films were Ga-rich. The N/Ga ratio estimated using AES spectra was recovered by increasing the substrate temperature. However, cheap substrates and low deposition temperatures are required for the application to ELDs with low cost processes. Thus optical properties of GaN films deposited at the low substrate temperature less than 550°C, which is a melting point of conventional glass substrate, are required for the application to ELDs. In this paper, properties of light emission as a function of the N/Ga ratio will be discussed. The N/Ga ratio of GaN films deposited at the substrate temperature higher than 400°C was dramatically improved. Cathodoluminescent (CL) spectra were also changed as increasing the N/Ga ratio. The spectra of GaN films deposited at low temperature below 400°C were broad, whose peaks were located around 500 nm. On the other hand, as increasing the N/Ga ratio, UV emission peaks were increased. Electroluminescent spectra of ELDs using GaN films as emission layers also included the UV emission at room temperature.

L6.32
Transferred to L8.3

L6.33
GaN CHANNEL WAVEGUIDES FOR 1.5 μM OPERATION. C.C. Baker, A.J. Steckl, Nanoelectronics Laboratory, University of Cincinnati, Dept. of Electrical and Computer Engineering and Computer Science, Cincinnati, OH.

Wide-band-gap III-N compound semiconductor material systems have attracted significant interest due to the potential for high temperature electronic devices and photonic devices operating in the visible and near-UV. They have also shown themselves to be suitable hosts for rare-earth (RE) elements such as Er and Pr which have transitions at the critical 1.3 and 1.5 μm optical communication wavelengths[1]. Er-doped GaN, in particular, has been shown to be relatively immune to the thermal quenching[2] seen in other Er-doped semiconductors and has the ability to incorporate significant concentration[3] of RE ions without precipitation and without quenching the photoluminescence (PL) or electroluminescence (EL) intensity. The basic viability of RE-doped GaN technology for light emitting photonic applications from the ultraviolet to the infrared has been previously reported[4,5]. To move toward next generation integrated optic systems involving GaN and RE-doped GaN, we have investigated the properties of planar and channel GaN optical waveguides in the visible and infrared regimes. While there have been numerous reports of GaN waveguide operation in the UV and visible regimes[6] this is believed to be the first report of quantitative loss measurements taken in the infrared regime for GaN channel waveguides. The refractive index, film thickness and effective indices of the guided modes of a planar structure were obtained using the prism coupling method. Channel waveguides were then fabricated using a Cl_2/Ar-based inductively coupled plasma (ICP). An etch rate of 400 nm/min was obtained using conditions optimized for waveguide fabrication. The optical loss of the channel waveguides was found to decrease with wavelength giving losses of 5.4 dB/cm at 633 nm, 4.6 dB/cm at 1300 nm and 4.1 dB/cm at 1500 nm. [1]A.J. Steckl and J.M. Zavada, Mater. Res. Bull., 24, 33 (1999). [2]M. Garter and A.J. Steckl, IEEE Trans. El. Dev., 49, 48 (2002). [3]D.S. Lee, J. Heikenfeld, A.J. Steckl, U. Homerich, J.T. Seo, A. Braud, and J.M. Zavada, Appl. Phys. Lett., 79, 790 (2001). [4]A.J. Steckl, M. Garter, D.S. Lee, J. Heikenfeld, and R. Birkahn, Appl. Phys. Lett., 75, 2184 (1999). [5]J. Heikenfeld and A.J. Steckl, Appl. Phys. Lett., 77, 3520 (2000). [6]T. Tanaka, K. Uchida, A. Watanabe and S. Minagawa, Electronics Letters, 32, 34 (1996).

L6.34
GROWTH AND FABRICATION OF HIGH REVERSE BREAKDOWN HETEROJUNCTION N-GaN: P- 6H-SiC DIODES. A.V. Sampath, A. Bhattacharyya, R. Singh, P. Lamarre[a], C.R. Eddy, T.D. Moustakas, ECE Department, Boston University, Boston MA; [a]Viatronix Inc., Waltham, MA.

Wide band gap semiconductors are attractive for developing high power switching devices because of their ability to operate at both

higher temperatures as well as higher frequencies than conventional Si. In this paper we report on the growth and fabrication of GaN/SiC np heterojunction diodes by depositing Si doped n-GaN films by plasma-assisted molecular beam epitaxy directly on SiC without the use of GaN or AlN buffers. Careful ex-situ and in-situ preparation of the Si terminated 6H- SiC surface was necessary to produce high quality diodes. Vertical circular diodes were fabricated with sizes varying from 200 microns to 1mm in diameter. Mesas were formed by ICP etching of the MBE deposited n- GaN layer using Cl2. A Ti/Al/Ni/Au metal stack was employed as an n-ohmic contact to the GaN layer and a Al/Ti/Au metal stack was employed as a back-side p-ohmic contact to the 6H- SiC layer. The diodes were characterized by I-V and C-V measurements. The 1 mm diameter diodes exhibited almost ideal behavior under forward bias with an ideality factor of 1.6, and a reverse saturation current of 10-19 A/cm2. Under reverse bias, these devices were driven up to 1000 V with a measured leakage current of 5x 10-7 A. and a dynamic resistance varying from 1010 to 109 ohms with increasing reverse bias. The built-in potential in these n-p heterojunctions was determined from C-V measurements to be 2.25 V. From these values we determined that the heterojunction is of Type II with conduction and valence bands offsets calculated to be 0.65 and 1.1 eV respectively.

L6.35
EDGE TERMINATION DESIGN AND SIMULATION FOR BULK GaN RECTIFIERS. K.H. Baik, University of Florida, Dept of Materials Science and Engineering, Gainesville, FL; Y. Irokawa, Toyota Central Research Laboratories, Aichi, JAPAN; Fan Ren, University of Florida, Dept of Chemical Engineering, Gainesville, FL; S. Pearton, University of Florida, Dept of Materials Science and Engineering, Gainesville, FL; S.S. Park, Y.J. Park, Samsung Advanced Institute of Technology, Suwon, SOUTH KOREA.

GaN bulk rectifiers show excellent on-state resistances (in the milli-ohm.cm-2 range), forward turn-on voltages of ~1.8V and reverse-recovery times of <50 ns. A key requirement is to develop effective edge termination techniques in order to prevent premature surface-induced breakdown. We have performed a simulation study of the effects of varying the dielectric passivation material (SiO2, SiNX, AlN, Sc2O3 or MgO), the thickness of this material, the extent of metal overlap onto the dielectric and the ramp oxide angle on the resulting reverse breakdown voltage (VB) of bulk rectifiers. We find that SiO2 produces the highest VB of the materials investigated, that there is an optimum metal overlap distance for a given oxide thickness and small oxide ramp angles produce the highest VB.

L6.36
PROPERTIES OF SURFACE ACOUSTIC WAVES IN AlN AND GaN. Jianyu Deng[a], Daumantas Ciplys[b], Gang Bu[c], Michael Shur[c] and Remis Gaska[a]; [a]Sensor Electronic Technology, Inc., Columbia, SC; [b]Vilnius University, Physics Faculty, Department of Radiophysics, Laboratory of Physical Acoustics, Vilnius, LITHUANIA; [c]CIEEM and Dept. of ECSE, Rensselaer Polytechnic Institute, Troy, NY.

Recent results on remote solar-blind SAW sensors have highlighted the importance of SAW in nitrides for novel acousto-opto-electronic device applications. The emergence of bulk AlN and GaN substrates has opened up a possibility to launch SAWs in GaN and AlN-based films with different crystallographic orientations, and, in this paper, we will present theoretical and experimental results on the effect of the crystal orientation on surface acoustic waves in AlN and GaN films. We solved the wave propagation equations in these materials using the continuity of electric field and mechanical stresses as the boundary conditions. This theory yields the SAW velocity and the electric field and mechanical displacement distributions. The electrical-mechanical coupling coefficient (K^2) is obtained by comparing the velocity in free surface and metal-covered surface material. Our results predict the values of K^2 of 0.13% and 0.22% for Z-cut surface propagation, for GaN and AlN bulk material, respectively. However, K^2 in AlN, can increase up to 0.8% in certain crystal orientations (Y-cut Z propagation, etc.), which indicates its strong potential in SAW applications. These results will be compared with the experiments that are now in progress.

L6.37
SURFACE ACOUSTIC WAVE RESONATORS FROM THICK MOVPE-GROWN LAYERS OF GaN(0001) ON SAPPHIRE. Sverre V. Pettersen, Thomas Tybell, Arne Rønnekleiv, and Jostein K. Grepstad, Dept of Physical Electronics, Norwegian University of Science and Technology (NTNU), Trondheim, NORWAY; Veit Schwegler, Dept of Optoelectronics, University of Ulm, Ulm, GERMANY.

The wide bandgap semiconductor GaN has been the centre of noticeable scientific attention over the last decade, mainly because of its successful application in short wavelength optical emitters, such as the blue laser diode and multicolour LEDs. Moreover, the piezoelectric properties of the group III-nitrides render this material system an interesting option for surface acoustic wave (SAW) devices. In this paper, we report on fabrication and measurement of a SAW resonator prepared on ~10μm thick films of GaN(0001). The films were grown by MOVPE on c-plane sapphire substrate. The morphology, chemical composition, and crystalline quality of the film surfaces were examined with AFM, SEM, XPS, and LEED. A metallic bi-layer of 15nm Ti and 300nm Al was subsequently evaporated on the nitride film surface. Definition of the resonator IDTs, designed with a wavelength of λ=8μm, was accomplished with standard UV lithography and lift-off. S-parameter measurements showed a resonator centre frequency of f_0=495MHz at room temperature, which corresponds to a SAW velocity of 3844m/s. The insertion loss at centre frequency was measured at 8.0dB, and the loaded Q-factor was found to be 2200. Finally, temperature dependent measurements in the range 25-155°C showed a TCF (temperature coefficient of frequency) of -18ppm/°C for this resonator.

L6.38
CHARACTERISTICS ANALYSIS OF SAW FILTER FOR MICRO-WAVE USING UNDOPED-GaN THIN FILM. Cheol-Yeong Jang, Min-Jung Park, Eun-Ja Jung, Hyun-Chul Choi, Jung-Hee Lee, Yong-Hyun Lee, School of Electronic Engineering & Computer Science, Kyungpook National University, Daegu, KOREA.

Acoustic wave devices are necessary for Contemporary mobile communication system. AlN, GaN, and their alloys are important piezoelectric 3- 5 semiconductors which are suitable for SAW (Surface Acoustic Wave) applications as well as blue//green light emitters and high power//high temperature transistors. The epitaxially grown GaN thin film was prepared by MOCVD (metal organic chemical vapor deposition) for SAW filter. GaN thin film had enough quality which are crystallinity, morphology, and etc. for SAW filter. The surface morphology and crystalline of the GaN thin films were characterized using SEM and X-ray rocking curve. SAW filter which was fabricated by lift-off process and frequency response was measured by HP 8753C network analyzer. Center frequency was 423.31 MHz and SAW velocity was 5079 m//s when wavelength(/lambda) was 12μm. Insertion loss was -25.662 dB and Q factor was 576.92, side lobe attenuation was over 13 dB which was enough for use SAW filter. Electro-mechanical coupling coefficient (k^2) was calculated from the measured data. k^2 was from 2.15%. The fabricated SAW filter using Undoped-GaN//sapphire structure has good quality for filter, and will be used Saw filter for operating RF frequency. This work was supported by grant No. 2000-2-30200-006-2 from the Basic Research Program of the Korea Science & Engineering Foundation.

L6.39
DEVELOPMENT OF A THIN FILM WIDE BANDGAP SEMICONDUTOR WAVEGUIDE FOR MICROFLUIDIC DRUG DELIVERY. Mona R. Safadi, Claudine A. Jaboro, Alexander L. Lagman, Gregory W. Auner, Wayne State University, Dept of Electrical and Computer Engineering/Biomedical Engineering, Detroit, MI; Daad Haddad, Yuri Danylyuk, Ratna Naik, Wayne State University, Physics Department, Detroit, MI.

The fabrication of a broad spectrum AlN thin film waveguide used in a caged neurotransmitter based microfluidic chip to direct ultraviolet light to microfluidic channels is reported. KrF Excimer laser micromachining technology is employed in the development of the wide band gap waveguide. Polycrystalline AlN thin films are grown on C-plane sapphire with high refractive index buffer layer by PSMBE, plasma source molecular beam epitaxy. A 248 nanometer laser beam is projected through a stainless steel mask patterned ten times larger than the actual size of the waveguide and through an objective onto the AlN/sapphire substrate. The irradiation energy per pulse, frequency or repetition rate, number of pulses, and thickness of film were varied, while the beam profile, wavelength and pulse duration were held constant. Wave-guide properties are efficiently characterized as a function of thickness, geometry and crystalline quality. Analytical measurements such as atomic force microscopy (AFM), confocal microscopy, and X-ray diffraction, were used to characterize the surface and crystalline structure. An optical pyrometer was used to measure the intensity of ultraviolet light through the waveguiding micro-channels. Through these techniques, the necessary parameters for the waveguide were determined. Preliminary results of UV optical fiber coupling efficiency was obtained. Results of a precise method in fabricating a prototype microfluidic waveguide system will be presented.

L6.40
OPTIMIZATION OF A Pd/AlN/Si THIN FILM STRUCTURE FOR HYDROGEN GAS SENSING. Wenjun Mo, K.Y.S. Ng, Dept. of Chemical Engineering and Materials Science, Wayne State University, Detroit, MI; E.F. McCullen, R. Naik, Dept. of Physics and Astronomy, Wayne State University, Detroit, MI; L. Rimai, G.W. Auner, Dept. of Electrical and Computer Engineering, Wayne State

University, Detroit, MI.

We have investigated the electrical characteristics, sensitivity and response time of a hydrogen sensor utilizing a Pd/AlN/Si(111) structure. Its electrical characteristics are those of an MIS capacitor where the AlN layer acts as the insulator. The devices responded to hydrogen, down to ppm concentrations in the surrounding flow; with a shift along the voltage axis of the capacitance vs. voltage (C-V) curve. The C-V curves, as well as the sensitivity and response time of devices with same geometry were reproducible at any chosen temperature and frequency, however they did depend on the thickness of the Pd gate. It was found that the capacitance change at any frequency) for the 25 nm thick Pd gate device was twice as large as that for the 400 nm thick Pd device (at the same frequency). When the hydrogen was switched off, the C vs. time measurements for both thin and thick devices clearly indicate two distinct time constants for the capacitance to return to its pre-hydrogen value; an initial fast drop in capacitance followed by a much longer decrease. For the thinner gate devices, however, the second period is significantly longer than for the thicker gate devices; leading to a total recovery time nearly twice that of the thicker gate devices. This suggests that the response might not be due simply to the disassociation of hydrogen molecules and subsequent diffusion of hydrogen atoms to the Pd/AlN interface, but also to the diffusion of the hydrogen (or protons) into the AlN layer itself where they might tend to get trapped. For the thinner gate devices, more hydrogen is able to diffuse into the AlN for a larger overall response, but this leads to an increase in the total recovery time as compared to that of the thicker gate devices.

L6.41
SELECTIVE GAS SENSORS BASED ON GaN LAYERS AND SnO_2/GaN HETEROSTRUCTURES. V. Popa, G. Korotchenkov, I.M. Tiginyanu and V. Brynzari, Laboratory of Low-Dimensional Semiconductor Structures, Technical Univ of Moldova, Chisinau, MOLDOVA; S.M. Hubbard and D. Pavlidis, Dept of Electrical Engineering and Computer Science, Univ of Michigan, Ann Arbor, MI.

The sensitivity of GaN layers and GaN/SnO_2 heterostructures to different gases (C_2H_5OH, CO, H_2, O_3, etc.) was studied. Unintentionally doped epitaxial n-GaN layers were grown by low pressure MOCVD method on c-plane sapphire using trimethylgallium and ammonia as precursors [1]. SnO_2 films were fabricated by spray pyrolysis techniques using $SnCl_4$ as precursor and support temperature about 380°C. The thickness of the porous oxide was of about 10 nm. Ohmic contacts (Ti-Au) were formed by thermal evaporation at 250°C with subsequent thermal annealing at 500°C in air. The sensitivity of GaN films with resistive structure to alcohol vapors proved to be 10 to 40 times higher than the sensitivity to CO and H_2. The maximum gas response was observed at 450°C, it being reproducible and fast enough. In particular, the response and recovery times did not exceed 10 s at the operation temperature 350°C. GaN/SnO_2 heterostructures exhibited diode characteristics. The gas response was explored under reverse polarization and the results showed that these structures possess the highest sensitivity to hydrogen. A model explaining the gas sensitivity of GaN films and GaN/SnO_2 heterostructures is proposed and the advantages of GaN based gas sensors are discussed. [1] S.M. Hubbard et al.: Mater. Sci. & Eng. B, 91/92 (2002) 336.

SESSION L7: UV EMITTERS AND DETECTORS
Chair: E. Fred Schubert
Wednesday Morning, December 4, 2002
Room 302 (Hynes)

8:30 AM *L7.1
GaN/AlGaN ULTRAVIOLET LIGHT EMITTERS: GOALS AND CHALLENGES. Paul Fini, Materials Dept., Univ. of California, Santa Barbara, Santa Barbara, CA.

Ultraviolet (UV) light emitters based on GaN/AlGaN heterostructures have immediate application in white lighting as well as remote detection of biochemical agents, for example. Although there have been some promising initial demonstrations of UV emission from these heterostructures, difficulties in achieving satisfactory output efficiency remain. The growth of smooth, planar AlGaN with high Al content is difficult due to low adatom surface mobility and strain-induced cracking. The fortuitous compositional clustering believed to enhance recombination efficiency in InGaN quantum wells (QWs) has not been observed in GaN or AlGaN QWs, and thus dislocations are more effective as non-radiative recombination centers. Another problem is presented by the quantum-confined Stark effect, which spatially separates within the QW, leading to a lowered radiative efficiency. Finally, the challenge in developing p-type GaN (and even more so, AlGaN) with a high hole concentration is quite difficult. Depositing low-resistivity p-GaN contact metals has also been quite problematic, due not only to the low hole concentration in p-GaN, but also the lack of a metal or alloy with a sufficiently high work function. In this presentation, various device and growth strategies that may mitigate, if not overcome, the above AlGaN-related challenges will be discussed. For the improvement of p-type AlGaN and GaN, the use of superlattices for enhanced hole generation, compositional grading to the p-contact layer, and novel contact-metal-dependent annealing schemes are considered. Achieving improved radiative efficiency will necessitate low threading dislocation densities and/or growth on non-polar faces of GaN such as the A-plane. The tensile strain of the device structure must be monitored and controlled to avoid cracking during growth, especially in layers with high Al mole fraction. It is believed that optimization of the above approaches will lead to viable high-efficiency AlGaN-based UV LEDs and laser diodes.

9:00 AM L7.2
A GaN-FREE LED STRUCTURE FOR HIGH UV-LIGHT EXTRACTION. Toshio Nishida, Naoki Kobayashi, NTT Basic Research Laboratories, NTT Corporation, Kanagawa, JAPAN; Tomoyuki Ban, NEL Technosupport, Kanagawa, JAPAN.

Recently, ultraviolet light (UV) sources based on nitride semiconductors are extensively studied. We have demonstrated intrinsically efficient UV light emitting diodes (LEDs) by introducing an AlGaN-based LED structure grown on a high-quality bulk GaN substrate. However, the GaN substrate is optically absorptive material for the emission wavelength shorter than 370 nm. On the other hand, LEDs consisting of a transparent media promise excellent performance, because they are free from the internal optical absorption. Therefore, we tried to fabricate a transparent UV-LED structure free from the GaN. We used high-quality AlN template layers prepared on sapphire substrates as starting wafers. We grew an AlN homoepitaxial layer, an undoped AlGaN buffer layer, and an AlGaN-based LED structure that is free from GaN. The p-type contact was formed by depositing a Pd/Au electrode directly on the p-type transparent cladding layer consisting of a short-period alloy superlattice (SPASL) $Al_{0.16}Ga_{0.84}N/Al_{0.2}Ga_{0.8}N$ (3-nm period). The transparency of the LED structure at the emission wavelength of 352 nm was confirmed by utilizing AlGaN-based UV-LEDs as spectroscopic light sources. In spite of the absorption due to the active layer, the LED wafer shows high transparency of about 90%. By comparing the emission intensity from the top of p-type semitransparent electrode, this LED was found to have output power two times higher than that of an LED on a GaN buffer layer. Further, the emission spectrum from the transparent LED shows optical fringes due to the interference between the top surface and the interface at the substrate surface. This also confirms the transparency of this LED. By measuring the output power from the bottom side, we obtained 1.1 mW output with the low injection current of 50 mA, and the maximum output power was 1.5 mW with the injection current of 70 mA under room-temperature CW operation.

9:15 AM L7.3
HOLE INJECTION AND CARRIER RECOMBINATION IN 280 NM DEEP ULTRAVIOLET LIGHT EMITTING DIODES AT ROOM AND CRYOGENIC TEMPERATURES. M. Shatalov, V. Adivarahan, J.P. Zhang, A. Chitnis, S. Wu, R. Pachipulusu, V. Mandavilli, and M. Asif Khan, Dept of Electrical Engineering, Univ of South Carolina, Columbia, SC.

We for the first time report the room and cryogenic temperatures (300K-10K) operation of an $Al_xIn_yGa_{1-x-y}N/Al_xGa_{1-x}N$ single quantum well (SQW) deep ultraviolet light emitting diode (LED) with a peak emission wavelength of 280 nm. For a 300 μm by 300 μm mesa type p-n junction device, the total room temperature series resistance of 25 Ω increases to about 35 Ω at 10 K. The high-hole injection at cryogenic temperatures is attributed to the formation of a hole-accumulation layer at the interface of the p-$Al_xGa_{1-x}N$/p-GaN layers, which cap the SQW active region. The hole-accumulation layer results from the large bandgap offsets and piezoelectric doping. The device structures were deposited over high quality n^+-$Al_xGa_{1-x}N$ (x=0.4, 2 μm thick) buffer layers over basal plane sapphire substrates using low-pressure metalorganic chemical vapor deposition. At room temperature, for the 280 nm band-edge emissions, a total pulsed power of 0.15 mW was measured for a pump current of 400 mA. At low temperature (10 K) this band-edge emission increases by a factor of 15. We attribute this to an increased radiative recombination rate, a suppression of the parasitic long-wavelength emission and an increased injected carrier density in the quantum well active region. Experiments show that 280 nm emitting LED with the output power of several milliwatts at room temperature can be achieved. Details of material and device fabrication and characterization will be presented. Data will also be presented to elucidate the mechanisms responsible for the current conduction, electron-hole pair injection and the 280 nm band-edge electroluminescence.

9:30 AM L7.4
NEW UV LIGHT EMITTER BASED ON AlGaN HETERO-

STRUCTURES WITH GRADED ELECTRON AND HOLE INJECTORS. M.A.L. Johnson, N.C. State University, Materials Science and Engineering Department, Raleigh, NC; J.P. Long and J.F. Schetzina, N.C. State University, Physics Department, Raleigh, NC.

This paper describes a new UV light emitting structure that addresses the problem of small carrier concentrations (particularly hole concentrations) and large band offsets in wide bandgap nitride heterostructures through the use of graded electron and hole injection layers. For light emission at 280-290 nm, a representative MQWSCH device might consist of an AlGaN MQW active region (280 nm emission) sandwiched between n-type and p-type AlGaN light guiding layers (265 nm absorption edge) and AlGaN cladding layers (250 nm absorption edge). In addition to large band offsets between appropriate ohmic contact metals and the corresponding AlGaN cladding layers (about 1.7 eV) there are severe doping issues: Maximum hole concentrations in the p-type AlGaN cladding layer may only be $10^{14}/cm^3$ or less. To circumvent these problems, the new heterostructure employs reservoirs of electrons and holes in n-type and p-type GaN together with thin (30 nm) graded and doped AlGaN layers that link the doped GaN layers to the correspondingly doped AlGaN cladding layers. Under forward bias, this new heterostructure injects electrons and holes into and through the corresponding AlGaN cladding layers and light guiding layers of the device to the active MQW region of the device where light emission occurs. By means of this majority carrier injection process, efficient light emission at short UV wavelengths occurs at small forward bias voltages. MOVPE was used to synthesize heterostructures of the type described above and LED mesa diodes were fabricated. Narrow (20-25 nm FWHM) UV light emission was observed at wavelengths less than 290 nm at forward biases of 8-10 V (20 mA). These experimental results provide a "proof-of-concept" for this new device structure, which can be employed for the development of both UV LEDS and laser diodes.

10:15 AM L7.5
MOCVD GROWTH OF AlGaN ALLOYS FOR 300nm LEDs. A.A. Allerman, A.J. Fischer, D.D. Koleske, K.H.A. Bogart, R.J. Shul, Steven R. Kurtz, J.J. Figiel, and K.W. Fullmer, Sandia National Laboratories, Albuquerque, NM.

Solid-state light sources between 290 to 340nm will be useful for various applications such as chemical/biological agent detection and UV curing. This requires the growth of AlGaN alloys with high mole fractions (40-80%) of Al. We have investigated the MOCVD growth of these alloys as a function of wafer rotation rate, V/III ratio, pressure and Group-III flux. As expected, growth rate was strongly affected by rotation rate, however, Al incorporation did not show any dependence. We observed that for V/III ratios between 500-2500 and for growth rates less 0.5mm/hr, growth rate and Al incorporation is linear with either Al or Ga source flux. Under these conditions, the Al/III ratio of the solid approaches the Al/III ratio in the gas phase. Using these conditions, deep ultraviolet light emitting diodes (LEDs) have been grown without binary GaN layers which absorb UV photons. An n-p-n structure was grown with a leaky, reverse-biased p?n junction that enables injection of holes into the active region. The active region is composed of three Al0.2Ga0.8N quantum wells with Al0.8Ga0.2N barriers. Short period superlattices were used in the n- and p-type cladding layers to enhance electrical conduction. The LED had an emission wavelength of 320 nm with a peak continuous wave output power of 17.8 mW at a current density of 1.7 A/cm2. Sandia is a multiprogram laboratory operated by Sandia Corporation, for the United States Department of Energy under Contract DE-ACO4-94AL85000.

10:30 AM L7.6
WIDE BAND-GAP LIGHT EMITTERS WITH IMPROVED HOLE INJECTION. S.M. Komirenko, K.W. Kim, Dept of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC; J.M. Zavada, U.S. ARO, Research Triangle Park, NC; V.A. Kochelap, Institute of Semiconductor Physics, Kiev, UKRAINE.

The difficulties in achieving high hole concentrations in group-III nitrides originate from high values of activation energy of acceptors. The average hole concentration can be increased in a p-doped nitride superlattice (SL). However, most of the holes ionized from the acceptors are localized inside the quantum wells (QWs) and cannot participate in vertical transport utilized in traditional light-emitting devices (LEDs). In this report we propose two novel solutions of the problem of hole injection enhancement in wide band-gap LEDs. Low-intensity emitters: The conventional LEDs can be modified by introducing a two-terminal hole injector that consists of a p-doped SL-base with two contacts. A bias voltage applied between these contacts provides lateral hole acceleration and increases the effective hole temperature. This results in significant enhancement of overbarrier hot-hole concentration. The proposed LED can be thought of as a three terminal device, where the hot-hole SL-injector is placed on the top of heterostructure with an intrinsic i-layer, and an n-doped region. In the report, we discuss parameters of the nitride-based hot-hole injectors and characteristics of the three terminal UV-LEDs. High-intensity lateral current pumped emitters: To achieve high-density electron-hole plasma (EHP) and interband population inversion in group-III nitrides, we propose a planar p-i-n structure created in selectively-doped SLs: a region doped with acceptors is followed in lateral direction by an i-region and, finally, by an n-region. Thermal activation of the dopants supplies carriers into the QW layers. The QW layers accumulate both types of free carriers and a lateral p-i-n structure is formed. When a voltage is applied, the planar double injection gives rise to both effects, injection of two-dimensional EHP and the interband population inversion in the i-region. We discuss properties of lateral current pumped UV LEDs and laser diodes. The work was supported in part by US Army Research Office.

10:45 AM L7.7
HIGH-POWER 325 NM LIGHT-EMITTING DIODE ARRAYS BY FLIP-CHIP PACKAGING. A. Chitnis, M. Shatalov, V. Adivarahan, J.P. Zhang, W. Shuai, S. Sun and M. Asif Khan, Department of Electrical Engineering, University of South Carolina, Columbia, SC.

We report the use of a flip-chip geometry to fabricate arrays of high-power light emitting diodes (LEDs) with peak emission at 325 nm. The device active region consisted of three $Al_{0.18}Ga_{0.82}N$ (110 Å)/$Al_{0.12}Ga_{0.88}N$ (35 Å) multiple quantum wells that were deposited (using MOCVD) over a 2 μm thick n^a-$Al_{0.2}Ga_{0.8}N$ buffer layer over basal plane sapphire substrates. These were capped with a p-$Al_{0.3}Ga_{0.7}N$ (200 Å) / p-GaN (500 Å) layer. 200 μm x 200 μm mesa type pn-junction devices were then fabricated using Ti/Al/Ti/Au and Ni/Au for the n- and the p-type contacts. At room temperature the unpackaged devices exhibited a turn on at 4.5V and a series resistance of about 30 Ω. Single devices were then diced from the wafer and were flip chip bonded to a high thermal conductivity AlN (k=175 W/m-K) carrier. The carrier was then mounted on a custom copper header and the 2x2 array was wire bonded in parallel. For it we measured a record dc output power of 840 μW at a pump current of 180 mA. Further increase of pump current resulted in power saturation. In the pulsed pumping mode we again measured a record power of 6.68 mW at a pump current of 1 A. These numbers to date are the highest reported powers for the shortest wavelength for III-N deep UV LEDs. Material, device fabrication and characterization data will be presented to elucidate the mechanisms responsible for the dc power saturation and the key factors controlling the conversion efficiency.

11:00 AM L7.8
MICRO-RAMAN SPECTROSCOPY: SELF-HEATING EFFECTS IN DEEP UV LIGHT EMITTING DIODES. A. Sarua, M. Kuball, H.H. Wills Physics Lab, Univ of Bristol, Bristol, UNITED KINGDOM; M.J. Uren, QinetiQ Ltd, Malvern, UNITED KINGDOM; A. Chitnis, J.P. Zhang, V. Adivarahan, M. Shatalov, and M. Asif Khan, Dept of Electrical Engineering, Univ of South Carolina, Columbia, SC.

Ultraviolet light emitting diodes (LED) based on GaN and its ternary alloy AlGaN are key devices for applications such as solid state white lightening and remote chemical sensing. Often grown on low thermal conductivity UV-transparent sapphire substrates, ultraviolet LEDs are prone to self-heating effects, i.e., temperature rises during operation, contributing significantly to the commonly observed saturation of light output power at relatively low input currents. Rather little, however, is known about the actual device temperature of an operating ultraviolet LED. Using micro-Raman spectroscopy temperature measurements were performed as function of input current on 325nm-$Al_{0.18}Ga_{0.82}N/Al_{0.12}Ga_{0.88}N$ multiple quantum well LEDs grown on sapphire substrates, flip-chip mounted on SiC for heat-sinking. Temperature maps were recorded over the active device area. Temperature rises of about 70°C were measured at input currents as low as 50mA (at 8V) for 200μm x 200μm size LEDs despite flip-chip mounting the devices. Temperature rises at the device edges were found to be higher than in the device center, indicative of current crowding effects. Finite difference heat dissipation simulations were performed and compared to the experimental results

11:15 AM L7.9
EPITAXIAL GROWTH FOR SOLAR-BLIND ALGAN PHOTODETECTOR IMAGING ARRAYS BY METALORGANIC CHEMICAL VAPOR DEPOSITION. Uttiya Chowdhury, Charles J. Collins, Michael M. Wong, Ting Gang Zhu, Jonathan C. Denyszyn, Jin Ho Choi, Bo Yang, Joe C. Campbell, and Russell D. Dupuis, The University of Texas at Austin, Microelectronics Research Center, Austin, TX.

Solar blind photodetectors, with a selective sensitivity to wavelength in the range of 250 to 300 nm are of high defense and commercial interest. Due to absorption in the ozone layer, light of these wavelengths is virtually absent at positions on the Earth surface and as a result, the photodetectors can operate in absence of a high background radiation. Research has been aimed towards

two-dimensional imaging arrays of high external quantum efficiency (EQE) back-illuminated $p-i-n$ photodetectors for convenience of integration with electronic drive circuitry. We have demonstrated significant increase in EQE by using a highly conducting $Al_{0.6}Ga_{0.4}N$ layer for the n-contact. A record EQE of 58.1% peaked at 274 nm under zero volt bias was obtained without using an anti-reflecting coating. The EQE was seen to have a slight voltage dependence: going up to 64.5% at 5V reverse bias. The responsivity had a drop-off by one order of magnitude for a wavelength change of 4 nm on both the shorter and longer wavelength side. The $p-i-n$ device structure consisted of 100 nm $Al_{0.6}Ga_{0.4}N:Si+$ n-contact layer/ grading/ 150 nm $Al_{0.45}Ga_{0.55}N:ud$ absorption region/ $Al_{0.45}Ga_{0.55}N:Mg$/ grading/ 25 nm GaN p-contact layer. The structure was grown by low-pressure metalorganic vapor deposition (LP-MOCVD) on both-side-polished c-plane sapphire substrate under a hydrogen pressure of 50 Torr and at a temperature of 1070C. Trimethyl gallium (TMGa, trimethyl aluminum (TMAl), ammonia, silane and bis-cyclopentadienyl magnesium (Cp_2Mg) were used as precursors. X-ray reciprocal space map showed that the $Al_{0.45}Ga_{0.55}N$ absorption region is almost completely strained to the bottom $Al_{0.60}Ga_{0.40}N$ layers. $P-i-n$ mesa diodes were fabricated using standard lithographic technique and EQE was measured with a broad ultraviolet (UV) illumination, standardizing with a UV-enhanced Si-photodetector of known responsivity. 256 × 256 arrays were fabricated from the epitaxial structure in which high EQE, high uniformity and high yield were simultaneously obtained.

11:30 AM L7.10
CRACK NUCLEATION IN AlGaN/GaN HETEROSTRUCTURES. Peter J. Parbrook, Malcolm A Whitehead, III-V Central Facility, University of Sheffield, Sheffield, UNITED KINGDOM; Robert T. Murray, Department of Materials Science and Engineering, University of Liverpool, Liverpool, UNITED KINGDOM.

The tensile strain in AlGaN layers on GaN is well established to lead to cracking if a critical thickness is reached, unless measures such as interlayers are applied to prevent their formation. Although much work has been applied to the understanding of cracks and to their elimination, much less is reported on the nucleation mechanisms involved. Growth of AlGaN-GaN structures was carried out by MOVPE using a standard two stage process for the growth of the GaN on sapphire. The crack structures were examined by optical and atomic force microscopy. Studies on thin AlGaN layers on GaN close to the crack critical thickness show the stress centres from which the cracks propogate are threading dislocations with cracks initially forming to link together these stress centres. These initial microcracks do not appear to necessarily follow the typically observed propagation direction at this stage. These cracks are observed to gradually extend and "lock" into the $<2-1-10>$ direction in more highly strained layers, except where they terminate near a preexisting crack propagating at 60 degrees to it, where a turn towards the normal of the preexisting crack's propagation direction is observed. A high macroscopically uniform crack array is observed in such samples. In more complex multilayer structures, with lower overall strain, cracks may preferentially nucleate from the wafer edge leading to a low density of cracks propagating across the wafer. In this case non-uniformities as the wafer edge are the likely source, and these may be substrate supplier dependent. In such cases the interaction between two cracks can lead to the one being bent and ultimately propagating in the $<1-100>$ direction over large distances.

11:45 AM L7.11
SOLAR-BLIND AlGaN-BASED SCHOTTKY PHOTODIODES WITH HIGH DETECTIVITY AND LOW NOISE. Necmi Biyikli, Orhan Aytur, Bilkent University, Dept of Electrical and Electronics Engineering, Ankara, TURKEY; Ibrahim Kimukin, Turgut Tut, Ekmel Ozbay, Bilkent University, Dept of Physics, Ankara, TURKEY.

We report on the design, fabrication and characterization of solar-blind Schottky photodiodes with high detectivity and low-noise. MOCVD-grown n-/n+ AlGaN/GaN hetero-structures on sapphire substrate were utilized. $Al_xGa_{1-x}N$ (x=0.38) absorption layer was used to achieve true solar-blind detection with a cut-off wavelength smaller than 280 nm. The detectors were fabricated using a four-step microwave compatible fabrication process. The ohmic and mesa isolation etch processes were accomplished using reactive-ion-etching with CCl_2F_2. A thin Au film was used as the Schottky contact layer. After device fabrication, I-V, spectral responsivity, and noise characteristics of the solar-blind detectors were analyzed. The resulting devices had breakdown voltages above 50 V and turn-on voltages around 2 V. 150×150 μm^2 area devices exhibited a dark current density lower than 1.8 nA/cm^2 at reverse bias voltages as high as 25 V. A dark impedance in excess of 10^{13} Ω was obtained in the 0-25 V range. A bias-dependent spectral responsivity was observed with a maximum responsivity of 0.09 A/W around 267 nm under 50 V reverse bias. True solar-blind operation was achieved with a cut-off wavelength of ~ 274 nm. The responsivity dropped sharply around 270 nm and a solar-blind/near-UV contrast of 4 orders of magnitude was observed within 80 nm. With a 0.01 A/W photovoltaic responsivity at 250 nm, the zero-bias detectivity of our detectors were in excess of 2.6×10^{12} cmHz$^{1/2}$/W, which corresponds to a set-up limited NEP of 5.8×10^{-15} W/Hz$^{1/2}$. The detector noise was 1/f limited with spectral noise density values less than 3×10^{-29} A^2/Hz under reverse bias voltages as high as 25 V. The dark current, peak responsivity, and detectivity values achieved with these devices correspond to the best detector performances obtained using solar-blind Schottky photodiodes.

SESSION L8: VISIBLE LIGHT EMITTERS
Chair: Christian M. Wetzel
Wednesday Afternoon, December 4, 2002
Room 302 (Hynes)

1:30 PM *L8.1
HIGH-POWER GaN-BASED LEDS FOR SOLID-STATE LIGHTING AND DISPLAYS. S.A. Stockman, A.Y. Kim, M. Misra, P. Grillot, L. Cook, R. Mann, W. Goetz, M.R. Krames, D. Steigerwald, D. Collins, P.S. Martin, J. Sun, S. Watanabe, Lumileds Lighting, San Jose, CA.

The luminous efficiency of visible LEDs (blue, green, and white) based on GaN now exceeds that of most conventional lighting technologies. However, power limitations (<0.1 W/LED) have limited adoption. We will review the current state-of-the-art in GaN LED technology, and highlight current challenges in MOCVD epitaxy, device design, and high-volume manufacturing. We will also describe recent developments in technology for high-power GaN-based LEDs which are operated beyond 1 W/LED with high efficiency (50 lm/W green, >30 lm/W white) and excellent reliability, and will preview future challenges in solid-state lighting and display applications.

2:00 PM L8.2
InGaN/GaN TUNNEL INJECTION BLUE LIGHT EMITTING DIODES. T.C. Wen, S.J. Chang, L.W. Wu, Y.K. Su, W.C. Lai, C.H. Kuo, C.H. Chen, J.F. Chen, Institute of Microelectronics & Department of Electrical Engineering, National Cheng Kung University, TAIWAN; J.K. Sheu, Optical Science Center, National Central University, TAIWAN.

A tunneling injection (TI) structure was applied to nitride-based blue light emitting diodes (LEDs) to enhance their output efficiency. The TI structure is to insert a wide electron emitter layer and a thin electron tunneling barrier in between the multiple-quantum-wells (MQW) active region and the n-cladding layer of the LED. Since the width of the electron emitter layer is large, electrons can be captured efficiently into the electron emitter layer. These captured electrons can subsequently tunnel through the tunneling barrier into the thin well layers of the MQW active region. Thus, one can achieve a large electron capture rate and a large carrier confinement effect simultaneously. In this study, we could decrease the 20mA forward voltage from 4.16V to 3.58V with a proper electron emitter layer. The lower forward voltage observed from the TI LEDs can be attributed to the InGaN electron emitter layer since the captured electrons will spread out in the in-plane direction before they tunnel into the MQW active region. As a result, we can achieve a better current spreading and thus a lower forward voltage for the TI LEDs. It was also found that with a 20nm-thick InGaN electron emitter layer, we could increase the LED output intensity from 28.3mcd to 43.2mcd (i.e. a 53% increase). However, a further increase in electron emitter layer thickness will reduce the intensity due to relaxation. The initial increase can be attribute to the increase of electron capture rate since more electrons can be captured when the electron emitter layer width is larger. However, when the electron emitter layer width is too large, the EL intensity decreases due to the relaxation induced defect generation and non-radiative recombination.

2:15 PM L8.3
GROWTH OF HIGH-x N-TYPE $Al_xGa_{1-x}N$ FOR SOLAR-BLIND PHOTODETECTORS. M. Pophristic, SP. Guo and B. Peres, EMCORE, Somerset, NJ; P. Lamarre, K.K. Wong, A. Hairston, J.S. Ahearn and M.B. Reine, BAE SYSTEMS, Lexington, MA and Nashua, NH; B. Yang and J. Campbell, Microelectronics Research Center, University of Texas, Austin, TX.

This talk presents progress in the MOCVD growth of n-type $Al_xGa_{1-x}N$ layers with aluminum mole fraction $x \geq 0.60$. Such layers are important as window and contact layers for solar-blind p-i-n photodiodes, and UV LEDs. Previously, it has been difficult to obtain n-type $Al_xGa_{1-x}N$ with aluminum mole fraction $x \geq 0.40$ that combined good crystallinity together with electron concentrations high enough for good n-side contacts. Our study shows that there is a narrow window of growth parameters for efficient silicon doping of high-x AlGaN. For optimum growth conditions, room temperature

Hall measurements of silicon-doped AlGaN epilayers with x~ 0.60 show electron concentrations from 1.5^{18} to 3.5×10^{18} cm^{-3}, and a mobility of ~ 25 cm^2/V-sThe full width half maximum of HRXRD rocking curves for all $Al_xGa_{1-x}N$ films was ~ 400 arcsec. The growth of mole fraction n-type AlGaN layers and the importance of buffer layers will be addressed in this paper. Solar-blind p-i-n AlGaN photodiodes were successfully fabricated using the improved n-type $Al_{0.6}Ga_{0.4}N$ layers. These devices had improved quantum efficiencies, up to 38% at 270 nm for -5 V reverse bias, along with low dark current densities of 2×10^{-9} A/cm^2 at -1 V and high $R_0A > 1.4 \times 10^8$ ohm-cm^2, all indicative of good film quality. This work is funded by BAE SYSTEMS as part of the DARPA Solar Blind Detector Program, managed by Dr. Edgar J. Martinez, under ONR Contract N00014-99-C-0138. The ONR COTR is Dr. Yoon-Soo Park.

3:00 PM L8.4
BLUE LIGHT EMITTING DIODES IN NANOMETER SCALE PATTERNED InGaN MEDIA. Lu Chen, A. Yin, J.S. Im, A.V. Nurmikko, J.M. Xu, Brown University, Division of Engineering and Department of Physics, Providence, RI; J. Han, Yale University, Department of Electrical Engineering, New Haven, CT.

The goal of our work is to explore the regime of enhanced spontaneous and stimulated emission in subwavelength patterned nitride structures for blue/ultraviolet light emitters. Such arrayed patterns of InGaN/GaN MQWs heterostructures were produced in a two-fold approach by electron beam lithography (100 nm feature size) and pattern transfer from self-organized porous alumina (50 nm). Spontaneous emission and light extraction of such subwavelength scale structure have been studied under high excitation optical pumping. A comparison of photoluminescence results between un-patterned and patterned arrays showed that the spontaneous emission efficiency from subwavelength structures is very robust and possibly enhanced. This is in strong contrast to conventional III-V and II-VI semiconductors, where surface recombination at the etch-exposed vertical walls of the QW is quite detrimental. To realize this enhanced emission efficiency in electrically injected subwavelength structures, light emitting diode type devices were designed and fabricated. We overcame the challenge of these deeply etched arrayed nanoposts by using spin-on-glass coating to planarize the structure and electrically isolate the nanoposts. LEDs based on these subwavelength structures were realized on the scale of 600nm. The wall plug efficiencies among different arrayed patterns were measured and compared. Several issues in the fabrication process are yet to be solved and the performance of these devices will be optimized soon. We are also working on devices based on smaller scale structures. Nanostructures on the scale of 100nm are designed to create photonic crystal bandgap, which forbidden the in-plane propagation of emitted light, and thus further enhance the light emission efficiency. LEDs with arrayed patterns on the scale of sub 50nm are being fabricated to investigate the possible enhancement of light emission due to near field dipole-dipole interaction.

3:15 PM L8.5
ENHANCED LIGHT EXTRACTION OF InGaN MQW BY SURFACE PLASMON. C.C. Lee, Optical Science Center, National Central University, Jung-Li, TAIWAN; C.Y. Chang, G.C. Chi, Department of Physics, National Central University, Jung-Li, TAIWAN; Y.L. Huang, Institute of Optical Sciences, National Central University, Jung-Li, TAIWAN; W.H. Lan, J.C. Lin, Y.D. Shiang, Chung-Sun Institute of Sciences and Technology, Lung-Tan, TAIWAN.

/Coupling of a multi-quantum well (MQW) and semitransparent metal layer is shown to result in dramatic enhancement of spontaneous emission rate in the optical spectral range. A five-pairs 10nm InGaN/GaN MQW is positioned 8 nm, form various thickness (t=5 20nm) silver layer. And periodic patterns (p=0.25 0.5um) are defined in the top semitransparent metal layer by e-beam lithography, which are antenna structures can be incorporated into the metal film. We have experimentally measured photoluminescence intensity of spontaneous emission of the fabricated structures up to 35 times higher than the unprocessed samples, whilst still ensuring that most of the emission takes place into the surface plasmon (SP) mode. And the implication of these results for extracting light from light emission diode is discussed.

3:30 PM L8.6
OPTICAL REFLECTANCE MEASUREMENTS OF THE 3D TO 2D DELAYED RECOVERY OF GaN ON SAPPHIRE WITH CORRELATION TO IMPROVED 380 nm LED BRIGHTNESS. D.D. Koleske, A.J. Fischer, A.A. Allerman, C.C. Mitchell, S.R. Kurtz, J.J. Figiel, K.W. Fullmer, and W.G. Breiland, Sandia National Laboratories, Albuquerque, NM.

GaN-based UV emitters are gaining interest as pump sources for developing white light emitting diodes (LED), and much research is currently focused on making these emitters more efficient. It is becoming evident that threading dislocations (TDs) may act as non-radiative recombination centers in the UV LEDs, where the In content and electron confinement in the quantum wells is less. This means that reducing TDs is essential for improving the light output in GaN-based UV LEDs. For this presentation, LEDs have been grown using MOVPE, while monitoring the optical reflectance. Following Figge et al., the transition from 3D-grain growth to 2D-coalesced growth was delayed in time by lowering the NH3 flow during the initial high temperature growth [1]. When low NH3 flows are used, the reflectance signal is near zero and the GaN film is composed of partly coalesced 3D grains. Eventually, the reflected light intensity recovers as the 2D morphology evolves. By intentionally delaying the recovery time from the rough 3D to 2D morphology, we observe a direct correlation between the reflectance recovery time and the LED light output. For LEDs fabricated on GaN films with a longer recovery times, we have achieved a 380 nm LED with an output power of 1.3 mW at 20 mA current. Evidence for dislocation reduction for films grown with a delayed recovery growth will be shown. We will also demonstrate how the individual growth steps can be tuned by monitoring the optical reflectance signal and by subsequently modifying growth parameters. [1]. Figge et al., J. Cryst. Growth 221, 262 (2000). *Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-ACO4-94AL85000.

3:45 PM L8.7
MULTISUBBAND PHOTOLUMINESCENCE FROM P-TYPE AlGaN/GaN SUPERLATTICES UNDER INTENSITY-DEPENDENT EXCITATION. Erik L. Waldron, E. Fred Schubert, Boston University, Dept of Physics and Electrical and Computer Engineering Department, Boston, MA; Amir M. Dabiran, SVT Associates, Eden Prarie, MN.

Photoluminescence spectra from modulation-doped $Al_{0.20}Ga_{0.80}N$/GaN superlattices with 10 nm well width show multiple, well resolved, interband transitions between quantum-confined states. In addition to the ground-state transition, a number of excited-state transitions are observed. The observation of multiple peaks is attributed to the inverse dependence of subband population and oscillator strength on energy. The relative strength of the peaks strongly changes with excitation intensity. At low excitation intensity, the spectra display only the ground-state transition. At higher excitation intensity, excited-state transitions become dominant. At high excitation intensities, the dominant transition occurs at energies about 500 meV above the electron ground-state to hole ground-state transition. Self-consistent calculations are used to assign transition energies, lifetimes, and rates to each photoluminescence line. Theoretical and experimental transition energies are in excellent agreement. We attribute the excellent optical properties to the modulated doping of the structure, which consists of doped barriers and undoped well layers. Our calculations also show an average recombination lifetime of 50 ns at high excitation intensities, despite the large quantum-confined Stark effect. The changes of the photoluminescence spectra can be explained via the effects of band filling and oscillator strengths at higher excitation intensity.

4:00 PM L8.8
FORMATION OF QUANTUM DOTS BY SELF-REARRANGEMENT OF METASTABLE 2D GaN. Noëlle Gogneau, Christoph Adelmann, Bruno Daudin, Eva Monroy, Jean-Luc Rouvière, Eirini Sarigiannidou CEA-Grenoble, Equipe mixte CEA-CNRS-UJF Nanostructures et Semiconducteurs, FRANCE.

The growth of GaN in very Ga-rich conditions results in the formation of a self-regulated Ga film, about 2 monolayers thick, on the growing surface. When GaN is deposited on AlN the presence of this Ga film deeply modifies the elastic strain relaxation mechanism. As a matter of fact, the usual Stransky-Krastanow (SK) growth mode giving rise to a 2D-3D transition is then completely inhibited and growth rather proceeds according to the Frank-Van der Merwe mode, with strain relaxation occuring by formation of misfit dislocations beyond a given critical thickness. However, when a GaN film grown in very Ga-rich conditions is let to evolve *under vacuum*, evaporation of the Ga film changes the total energetic balance of the system and leads to the formation of 3D GaN quantum dots.
This new GaN dot formation mechanism has been studied as a function of various relevant parameters: nominal thickness of the 2D GaN layer, temperature of Ga evaporation, ripening time after 3D islanding. Atomic force microscopy, transmission electron microscopy, cathodo- and photoluminescence have been performed.
It has been foud that dot density could be varied by more than one order of magnitude by changing the thickness of 2D GaN layer, from about 10^{10} cm^{-2} to more than 10^{11} cm^{-2}. Intense photoluminescence was observed at room temperature, as an indication of very efficient radiative recombination in dots formed according to the rearrangement method.
Finally, we propose a model to describe the hierarchy of plastic/elastic

strained nitride heterostructures as a function of kinetical parameters (growth temperature and Ga/N ratio value) and discuss the way to elaborate at the grower's choice either quantum wells or quantum dots depending on requested physical/technological purposes.

4:15 PM L8.9
SELF-ASSEMBLED GaN QUANTUM DOTS ON 6H-SiC(0001) SUBSTRATES. C.-W. Hu, A. Bell, D.J. Smith, F.A. Ponce, and I.S.T. Tsong, Arizona State University, Department of Physics and Astronomy, Tempe, AZ.

We report the fabrication of nanometer-scale GaN quantum dots (QDs) via the formation of Ga liquid droplets and their subsequent nitridation with a supersonic gas source seeded with NH_3 molecules. The growth of the self-assembled GaN QDs takes place on 6H-SiC(0001) substrates and the process is based on the vapor-liquid-solid (VLS) mechanism. In contrast to the conventional Stranski-Krastanov growth mode usually employed for the growth of Group III nitride nanostructures, the VLS approach allows easy manipulation of the kinetic parameters to control the size and spatial distributions of the Ga droplets to be nitridized. The Ga droplets were deposited on the substrates surface at 300-550°C and the nitridation by the NH_3 flux was conducted at 450-600°C. The entire process was observed and controlled *in situ* and in real time in the low-energy electron microscope (LEEM). The size and density of the self-assembled QDs were further confirmed by atomic force microscopy (AFM) images taken *ex situ*. Cross-sectional transmission electron microscopy (XTEM) images of the GaN QDs show a completely defect-free 2H-wurtzite structure. Spatially resolved cathodoluminescence (CL) spectroscopy was conducted on the QD-array as well as individual QDs. The characteristic band-edge emission at 3.47 eV was observed for all QDs and the amount of blue-shift was found to vary for each individual QD.

4:30 PM L8.10
MBE GROWTH OF HIGH-QUALITY QUATERNARY InAlGaN THIN FILMS AND QUANTUM WELL HETEROSTRUCTURES. Alexandros Georgakilas, Emmanuel Dimakis, Maria Androulidaki, Katerina Tsagaraki, Nikolaos T. Pelekanos, FORTH and University of Crete, Heraklion, GREECE; Philomela Komninou, Aristotle University of Thessaloniki, Thessaloniki, GREECE; Denis Jalabert, Edith Bellet-Amalric, CEA, Grenoble, FRANCE.

We will present results showing that high quality quaternary InAlGaN alloys and quantum well (QW) heterostructures can be grown by plasma-assisted MBE on Ga-polarity GaN-on-sapphire (0001) substrates. An RF nitrogen plasma source and solid Ga, Al and In sources were used. The Al and Ga fluxes were chosen to have a 2:3 ratio so that the corresponding AlGaN alloy would consist of 40% Al and 60% Ga, and quaternary InAlGaN alloys were then grown with In incorporation in the range of 0-11% as determined by RBS. The corresponding bandgap covered the range from 4.2eV down to 2.9eV at 20K. We determined the growth temperature dependence of the In incorporation in the InAlGaN alloy and we controlled the alloy composition by varying either the growth temperature or the In flux. The MBE growth of the InAlGaN layers was optimized by selecting substrate temperature and In fluxes that ensured a layer-by-layer growth mode under In-stabilized surface conditions, with limited In accumulation on the surface and significant In incorporation. A specific methodology was developed for the precise and reproducible tuning of the growth parameters. InAlGaN layers of a 250nm thickness exhibited surfaces with rms roughness as low as 0.7nm. All samples exhibited intense band-edge photoluminescence up to 300K with linewidths as low as 73meV at 3.25eV, while a large In bandgap bowing parameter was determined. The good structural quality of the layers was confirmed by High resolution XRD and TEM. Finally, high quality InAlGaN/GaN QW heterostructures were grown as evidenced by the observation of abrupt interfaces in TEM images and the appearance of sharp diffraction satellite peaks and interference fringes in XRD measurements. The growth process was optimized to eliminate any unwanted In-incorporation in the GaN layers by In-segregation effects and the first optically-pumped lasing results were obtained at 300K.

4:45 PM L8.11
RAPID THERMAL MOCVD GROWTH OF GaN AND InGaN LAYERS. O. Kreinin, G. Bahir, and J. Salzman, Technion-The Israel Institute of Technology, Department of Electrical Engineering, Solid State Institute, and Microelectronics Research Center, Haifa, ISRAEL.

Growth of InGaN-GaN heterostructures requires cyclic ramping of the growth temperature of ~200°C. In conventional MOCVD this temperature ramping is slow, and part of the InGaN layer may degrade before next GaN layer is deposited. In order to prevent such degradation, it would be beneficial to have a "rapid thermal" process to provide the additional ~200°C in a short time interval. Rapid Thermal MOCVD (RT-MOCVD) appears to be a feasible solution. By using a series of lamps to radiatively heat only a low thermal mass susceptor, it is possible to achieve wafer temperature ramp rates of ~250°C/s. This allows the fabrication of heterostructures by using temperature as a switch in starting or terminating a process step rather than applying the gas phase switching technique used in the conventional MOCVD. Here, we demonstrate the growth of GaN and InGaN single layers on sapphire substrates in a RT-MOCVD reactor. It is shown that in our growth system, the use of the temperature switch method provides a higher quality GaN and InGaN layers than by use of gas phase switching. A low pressure, load lock, horizontal and laminar flow reactor, heated by two sets of high power lamps was used for this work. Trimethylgallium, trymethylindium and ammonia were used as precursors for Ga, In and N, respectively; H_2 and N_2 as the carrier gases. The growth temperatures for the buffer layer and the main GaN layer were ~540°C and ~1050°C, respectively; for InGaN layer ~780°C. The reactor pressure was kept at the range 70-700 Torr. Photoluminescence, X-Ray diffraction, SEM and AFM microscopy were used for characterization of grown layers. Details of growth conditions and characterization of grown layers will be presented. The present work demonstrates that Rapid Thermal MOCVD is useful as a tool for the epitaxial growth of GaN and InGaN.

SESSION L9: ELECTRONIC DEVICES
Chair: Angela Rizzi
Thursday Morning, December 5, 2002
Room 302 (Hynes)

8:30 AM *L9.1
MATERIAL AND DEVICE ISSUES OF AlGaAn/GaN HEMTs ON SILICON SUBSTRATES. P. Kordos, P. Javorka, M. Marso, M. Wolter and A. Fox, Institute of Thin Films and Interfaces, Research Centre Jülich, GERMANY; A. Alam and M. Heuken, Aixtron AG, Aachen, GERMANY.

Selected material and device issues related to the preparation and performance of AlGaN/GaN HEMTs on (111)Si substrates will be presented. Virtually crack-free AlGaN/GaN material structures (x_{AlN} = 0.23) with good surface roughness (rms of 0.64 nm), n_s = (6-9)×10^{12} cm^{-2} and μ = 700-920 cm^2/V s at 300 K, were grown by LP-MOVPE on 2-inch (111)Si substrates. Unpassivated HEMTs with Lg = 0.3-0.7 μm were prepared by conventional device processing steps. Round-HEMTs as quick devices were used to evaluate the material structures. Significant difference in DC performance is found for devices prepared on different structures with nearly identical Hall data. Photoionization spectroscopy measurements show that two distinct trap levels of 3.2 and 2.9 eV, however with different cross section values, are present in all structures. It is assumed that the traps are surface related states. On the other hand, backgating studies performed at various substrate biases and illumination energies show that several traps contributions can be resolved. A new method based on DC-f(T) measurements is used to study self-heating effects. The HEMT channel temperature increases with dissipated power much slower than for devices on sapphire substrates (e.g. 95 and 320°C for HEMTs on Si and sapphire, respectively, at 6 W/mm). On the base of these studies high-performance AlGaN/GaN/Si HEMTs were prepared, which exhibit saturation currents up to 0.91 A/mm, a good pinch-off, a peak extrinsic transconductances up to 125 mS/mm and static heat dissipation capability up to ~16 W/mm. Unity gain frequencies fT up to 32 GHz and maximum frequencies of oscillation fmax up to 27 GHz were obtained. The saturation current and fT values are comparable to those known for similar devices using sapphire and SiC substrates.

9:00 AM L9.2
HIGH-QUALITY AlGaN/GaN HEMTS GROWN BY MBE ON SEMI-INSULATING 6H AND 4H SILICON CARBIDE. M.J. Manfra, N.G. Weimann, K.K.W. Baldwin, and J.W.P Hsu, Bell Laboratories, Lucent Technologies, Murray Hill, NJ.

Semi-insulating (SI) SiC is now widely used as a substrate for the molecular beam epitaxy (MBE) growth AlGaN/GaN heterostructures. The superior thermal conductivity of SiC compared to sapphire has clear advantages for high power high electron mobility transistors (HEMTs). Despite recent impressive device results, little has been reported concerning the MBE growth conditions that produce high quality AlGaN/GaN heterostructures on SiC substrates. In particular, little correlation has been made between MBE growth conditions and the phenomena of current collapse under large-signal RF operation. We have explored the MBE growth of AlGaN/GaN heterostructures nucleated directly on semi-insulating 6H and 4H SiC substrates. We discuss the efficacy of various nucleation schemes and the differences needed for each polytype. Using a simple two-step growth process, we routinely achieve room temperature mobility 1400cm^2/Vs at a sheet density of 1.2x$10^{13}$$cm^{-2}$, leading to sheet resistances between 330 and 400Ω/square. Transistors fabricated on our material are defined by

optical lithography. Device isolation is established by a mesa dry etch. Drain and source ohmic contacts are deposited and then alloyed, and finally a metal gate is deposited directly on the semiconductor surface. Typical devices have a periphery of 200μm, a source drain spacing of 6μm and a gate length of 2μm. Devices fabricated from this material display maximum drain currents in excess of 1.2A/mm. In addition to DC characterization, we have performed large signal power measurements to correlation MBE growth conditions with RF large signal performance. MBE grown devices display saturated output power densities in excess of 5W/mm CW at 2GHz in linear class A operation with minimal current collapse. We discuss the MBE growth conditions found to minimize current collapse.

9:15 AM L9.3
AlGaN/GaN HETEROSTRUCTURE FIELD-EFFECT TRANSISTORS WITH BACK-DOPING DESIGN FOR HIGH-POWER APPLICATIONS: HIGH CURENT DENSITY WITH HIGH TRANSCONDUCTANCE CHARACTERISTICS.
Narihiko Maeda, Kotaro Tsubaki, Tadashi Saitoh, Takehiko Tawara, Naoki Kobayashi, NTT Basic Research Laboratories, NTT Corporation, Kanagawa, JAPAN.

In the conventional AlGaN/GaN heterostructure field-effect transistors (HFETs) with modulation doping design, as the thickness of the AlGaN layer is reduced for higher device performance, possible carrier supply from the barrier layer is decreased and comes to be less than the inherent large capacity for the two-dimensional electron gas (2DEG) density. As a novel structure to overcome this situation, we have fabricated HFETs with the back-doping (BD) design where an asymmetric double-heterostructure is employed and doping is performed not only in the surface-side of the AlGaN layer but also in the back-side of the AlGaN layer whose Al compositions are designed to be relatively small. By using this structure, we have achieved high 2DEG densities for small AlGaN layer thickness, and have achieved both high drain-current densities and high transconductance (gm). We have grown BD-HFETs by MOVPE, whose structures are as follows: (4nm undoped/5nm Si-doped/3nm undoped)Al0.3Ga0.7N/25nm undoped GaN/10nm Si-doped Al0.09Ga0.11N/1um AlGaN/AlN buffer/SiC substrates. No abrupt discontinuity of Al compositions was made beneath the GaN channel to avoid additional accumulation of 2DEG. The BD-HFET exhibited very high 2DEG densities with relatively high 2DEG mobilities, i.e., 2.8e13 cm-2 (850 cm2/Vs) at room temperature, and 2.0e13 cm-2 (5000 cm2/Vs) at 77K. Reduction in the 2DEG mobility generally observed along with the increase in the 2DEG density was small in DB-HFETs. The fabricated BD-HFETs with the gate length of 1.5um exhibited high drain-current densities (Id) above 1000 mA/mm, and what should be emphasized is that high gm around 180 mS/mm were obtained at these high Id around 1000 mA/mm. These characteristics contrast with those of conventional HFETs that gm is reduced at high Id. These characteristics in BD-HFETs are ascribed to their 2DEG properties that the 2DEG mobilities are relatively high at very high 2DEG densities. Thus, BD-HFETs have high potentiality for high-power applications.

9:30 AM L9.4
HIGH-QUALITY AlGaN/GaN HFET STRUCTURES GROWTH BY MOCVD USING AN INTERMEDIATE HIGH TEMPERATURE AlGaN/GaN SUPERLATTICES. Alexander Demchuk, Gordon Munns, Peter Nussbaum, Don Olson, Andy Strom and Anil Jain, APA Optics, Inc, Blaine, MN.

We report on device quality AlGaN/GaN heterostructures growth by LP-MOCVD using intermediate AlGaN/GaN superlattices. A conventional low-temperature AlN buffer layer and insulating GaN epitaxial layer were first deposited on (0001) sapphire or 6H-SiC (0001) substrates. The 5 periods AlGaN/GaN superlattice then was deposited without any growth interruption at the same temperature as GaN has been grown. The sample was finished with another high-temperature GaN epitaxial layer, AlN/AlGaN spacer, silicon doped $Al_{0.28}Ga_{0.72}N$ film and undoped cap. It is well known that 2DEG mobility in AlGaN/GaN heterostructure is closely linked to interface planarity and dislocation density. In this heterostructures the edge and threading dislocations were efficiently filtered at the AlN/GaN superlattice interfaces. Thereby, further reduction of dislocations was achieved. Insertion of AlN/AlGaN spacer layer has been shown to reduce alloy scattering at the interfaces. The heterostructures grown with the optimized AlGaN/GaN superlattices exhibited mirror-like surface morphology. High-quality AlGaN/GaN heterostructures have been confirmed with X-ray analysis by measurement of mosaic twist in growth film, SEM with selective etching and Van der Pauw Hall measurements. The increase of room temperature 2DEG mobility from 1200 $cm^2V^{-1}s^{-1}$ to 1600 $cm^2V^{-1}s^{-1}$ was obtained at the sheet carrier density of 10^{13} cm^{-2} on heterostructures with AlGaN/GaN superlattice grown on sapphire and to 2000 $cm^2V^{-1}s^{-1}$ on SiC substrates. Correlation of DC microwave HFET device performance will be presented.

9:45 AM L9.5
AlGaN/GaN HETEROJUNCTION FAT FET DRIFT MOBILITY MEASUREMENTS AND VOLTAGE DEPENDENCIES. O. Katz, A. Horn, V. Garber, B. Meyler, G. Bahir, and J. Salzman, Department of Electrical Engineering and Microelectronics Research Center, Technion, Israel Institute of Technology, Haifa, ISRAEL.

GaN based heterojunction field-effect-transistors show great advantages for high power microwave applications. The transport properties of two-dimensional electron gas (2DEG) at the AlGaN/GaN interface are usually characterized by their Hall-mobility. However, the device high frequency performance depends directly upon the drift mobility. In addition, the dependence of the carrier mobility on the transistor voltage regime has not been investigated yet. We have grown high quality AlGaN/GaN heterostructures with measured room-temperature Hall mobility and sheet carrier concentration of 1750 cm^2/Vs and $9x10^{12}$ cm^{-2}, respectively. We have fabricated HFETs using Fat FET geometry. The Fat FET geometry consists of a large gate suitable for capacitance measurements, allowing us to assume a constant mobility model and ignore the parasitic resistance. We show three different techniques for measuring 2DEG mobility i) Hall effect ii) magnetoresistance iii) capacitance-conductance. While Hall effect was measured under the Van-Der Pauw configuration, we used the Fat FET for measuring both magnetoresistance and capacitance-conductance. Another advantage of these two methods is the ability to find the mobility dependence on transistor voltage, thus knowing the exact mobility at the transistor working point. Changing the drain-to-source voltage, we show the relation between electric field and the 2DEG mobility. Changing the gate-to-source voltage, we show the effect of the carrier concentration on the their mobility. Further, we discuss the differences between mobility measured in each technique, and relate them to scattering mechanisms under the relaxation time approximation.

10:30 AM L9.6
HIGH PERFORMANCE HFET DEVICES ON SAPPHIRE AND SiC: PASSIVATION WITH AlN. J.A. Bardwell, J.B. Webb, H. Tang, and Y. Liu, National Research Council Canada, Institute for Microstructural Sciences, Ottawa, ON, CANADA.

AlGaN/GaN two dimensional electron gas (2DEG) heterostructures were grown by ammonia-MBE on sapphire and SiC substrates. A crucial factor in obtaining high performance devices is the use of a semi-insulating C-doped GaN layer with resistivity greater than 10^6 Ω-cm. HFET structures grown on the C:GaN templates had excellent isolation characteristics as evidenced by the low dispersion in the open pad capacitance ($<3 \times 10^{-18}$F/μm^2). Devices fabricated from these optimized HFET layers, with optically defined gates showed excellent characteristics, e.g. a maximum drain current density of 1.3 A/mm, maximum transconductance of 220 mS/mm, f_T of 15.6 GHz and f_{MAX} of 58.1 GHz was measured for devices with 0.9 μm gate length and 40 μm gate width. However, these devices were subject to "current slump" when subjected to load pull measurements. Current slump was also observed in sequentially repeated DC measurements in the dark, both on sapphire and SiC substrates, although the degree of slump varied greatly from one wafer to another. One method of reducing the current slump was to apply a thin (~50 nm) magnetron sputtered AlN passivation layer (over the gates) or a similar layer under the gates so that MISFET devices were obtained. The electrical characteristics of the passivated and unpassivated devices will be discussed in detail.

10:45 AM L9.7
SELF-HEATING EFFECTS IN MULTI-FINGER AlGaN/GaN HFETs. M. Kuball, S. Rajasingam, A. Sarua, University of Bristol, H.H. Wills Physics Laboratory, Bristol, UNITED KINGDOM; M.J. Uren, T. Martin, R.S. Balmer, B.T. Hughes, K.P. Hilton, QinetiQ Ltd, Malvern, UNITED KINGDOM.

Power AlGaN/GaN HFETs are being developed for next generation mobile communication basestations, radars and satellite communication, where RF output powers exceeding 30-100W are required. These devices employ compact, multi-finger designs, which can show significant self-heating induced thermal cross-talk between fingers. This effect is normally only simulated rather than measured, despite its importance for power performance and ultimately device reliability. This is because direct measurement of device temperature is not readily achieved with the often employed infrared techniques due to their limited spatial resolution of 10-15μm when compared with the only micron-size source-drain opening in AlGaN/GaN HFETs. We report on the in-situ measurement of temperature, i.e., self-heating effects, in multi-finger AlGaN/GaN HFETs grown on SiC substrates. Optical micro-spectroscopy was used to measure temperature with 1μm spatial resolution. Thermal resistances (temperature rise per W/mm) as large as 19.5°C/(W/mm) were measured for 250μm-wide multi-finger AlGaN/GaN HFETs of 25μm device pitch (spacing of

gate fingers). This is significantly larger than the 7.7°C/(W/mm) reported recently in [1] for single-finger AlGaN/GaN HFETs. There is significant thermal cross talk in multi-finger AlGaN/GaN HFETs and this needs to be seriously considered for device design and ultimately device reliability. Thermal resistance was investigated as function of device pitch and gate finger width. A comparison with theoretical models of temperature distribution is presented. Acknowledgement: The QinetiQ contribution to this work was undertaken as part of the UK MoD Corporate Research Program. [1] M. Kuball, J.M. Hayes, M.J. Uren, T. Martin, J.C.H. Birbeck, R.S. Balmer, and B.T. Hughes, IEEE Electron Dev. Lett. **23**, 7 (2002).

11:00 AM L9.8
SPIN SPLITTING IN AlGaN/GaN HETEROSTRUCTURES. Jacek A. Majewski, Peter Vogl, Walter Schottky Institute and Physics Department, Technical University of Munich, GERMANY.

We present first-principles calculations of the zero field spin splitting of electrons and holes in bulk nitrides and AlGaN/GaN heterostructures and superlattices. GaN has recently been considered as promising material for spintronics. The spin life time in semiconductor structures is determined by the spin-orbit interaction induced spin splitting and the k-linear contributions are of the great importance. One of the origin of the k-linear zero-field spin splitting is Rashba effect. However, its magnitude, physical origin, the role of interfaces, and dependence on macroscopic electric fields are not fully understood. We have studied the spin splitting in the conduction and valence bands by performing fully relativistic pseudopotential local density functional calculations of cubic as well as wurtzite GaN/AlGaN superlattices. For cubic [001] superlattices with D_{2d} symmetry, the Rashba effect disappears and the k-linear zero-field spin splittings are entirely caused by the Bulk Inversion Asymmetry (BIA) term that originates from the bulk Dresselhaus term. In [111] cubic heterostructures the Rashba constants α_R are typically smaller than BIA constants α_{BIA}. The wurtzite GaN/AlGaN heterostructures constitute very interesting system for studing the Rashba effect. In wurtzite structure, in contrast to the cubic one, the Rashba effect is already present in bulks. The calculations for wurtzite GaN and AlN give the value of Rashba constant α_R equal to 0.008 and 0.004 eVÅ, respectively. Owing to the huge pyrroelectric and piezoelectric intrinsic fields (of the order of MV/cm), the Rashba constants are considerably enhanced in GaN/AlGaN wurtzite heterostructures and are much larger than in cubic systems. The calculations shed light on the physical origins of the Rashba effect and clarifies its strong dependence on the local microscopic structural details of the interface rather than the macroscopic electric fields. Noticeably, we find very large k-linear spin splittings between energetically close lying valence bands of wurtzite GaN. Through folding, these huge splittings are also present in quantum wells of corresponding width. Furthermore, using the obtained spin splitting constants, we discuss the corresponding spin relaxation rates in nitride heterostructures.

11:15 AM L9.9
InGaN CHANNEL DOUBLE HETEROSTRUCTURE FIELD – EFFECT TRANSISTORS: DC, PULSE AND RF CHARACTERISTICS. H.-M. Wang, J.-P. Zhang, A. Koudymov, S. Saygi, H. Fatima, G. Simin, J. Yang, and M. Asif Khan, Department of Electrical Engineering, Univ. of South Carolina, Columbia, SC; X. Hu, A. Tarakji, M.S. Shur, and R. Gaska, Sensor Electronic Technology, Inc., Latham, NY.

We for the first time present a comprehensive study of Schottky- and Insulating gate AlGaN/InGaN/GaN double heterostructure field-effect transistors (DHFETs) on sapphire and SiC substrates. In the DHFETs, the 2D electron gas (2DEG) channel is confined within 50 Å thick InGaN layer sandwiched between GaN buffer and AlGaN barrier. Significantly reduced electron spillover and the partial compensation of the strain modulation in the AlGaN/InGaN bilayer structure decrease the total trapped charge. This eliminates the current collapse observed in conventional GaN-AlGaN HFETs. In addition combining DHFET design with an insulating gate (a thin SiO_2 or Si_3N_4 layer under the gate) we were able to reduce the gate leakage by in 4-6 orders of magnitude while maintaining or even increasing the saturation current. The stable output RF power of above 7 W/mm was achieved in MOSDHFETs. In this talk the pulsed $I-V$ characteristics of DHFETs over SiC and sapphire substrates measured at different load impedances are compared to DC results as well as to high power RF load-pull data proving the absence of both gate- and drain lag in this novel device type. Comparative study of on-wafer and flip-chipped DHFETs and MOSDHFETs over sapphire substrates shows a very high potential of this approach for low-cost high power current collapse free devices.

11:30 AM L9.10
GATE CURRENT AND ANALYTICAL MODELING IN INSULATING GATE III-N HETEROSTRUCTURE FIELD EFFECT TRANSISTORS. Frederick W. Clarke, U.S. Army Space and Missile Command Technical Center, Huntsville, AL; Fat Duen Ho, Department of Electrical and Computer Engineering, The University of Alabama in Huntsville, Huntsville, AL; M. Asif Khan, Grigory Simin, J. Yang, Department of Electrical Engineering, The University of South Carolina, Columbia, SC; Remis Gaska, Sensor Electronics Technology Inc., Latham, NY; and Michael S. Shur, ECSE Department, Rensselaer Polytechnical Institute, Troy, NY.

Gate current plays an important role in determining the characteristics and limiting performance of GaN-based field effect transistors. In GaN-based HFETs, the gate current limits the gate voltage swing and, hence, the maximum device current. Since the electron transport across the wide band gap barrier layer involves trapping, under certain bias conditions, the gate current leads to the threshold voltage shifts and causes reliability problems. Under reverse bias, the gate leakage in GaN-based HFET dominates the minimum (pinch-off) drain current. Insulating gate HFETs (i.e. Metal Oxide Heterostructure Field Effect Transistors - MOSHFETs) have the gate leakage currents 4 - 6 orders of magnitude lower than HFETs, even at elevated temperatures up to 300°C. In this paper, we report on the gate current characteristics in these devices at room and elevated temperatures. We apply a comprehensive analytical model to these results that was previously developed and published in IEEE Transactions on Electron Devices (1992) for silicon based MIS devices. The effects of surface states, silicon dioxide thickness, substrate doping, fixed oxide charges, substrate thickness, and metal work function are taken into account. The form of the I-V characteristic curves for the leakage current in these GaN-based MOSHFETs is very similar to that obtained for their silicon analogs. We compare the measured data with the thermionic field emission theory and extract the electron transport parameters. We also report on the effects of the temperature stress (up to 800°C) on MOSHFET gate current, which increases the gate leakage by several orders of magnitude and interpret the results in terms of electron trapping by deep traps in wide band gap barrier layer. This mechanism is similar to that in silicon MOSFETs. Our data also show that, at elevated temperature, the pinch-off current in MOSHFETs is dominated by thermionic emission over the potential barrier between the source and drain. These results are important for possible applications of GaN MOSHFETs in non-volatile memory devices and integrated circuits that will operate in a much wider temperature range than conventional silicon non-volatile memories.

11:45 AM L9.11
DELTA-DOPED AlGaN/GaN METAL OXIDE SEMICONDUCTOR HFETs WITH HIGH BREAKDOWN VOLTAGES. Z.Y. Fan, J. Li, J.Y. Lin, and H.X. Jiang, Department of Physics, Kansas State University, Manhattan, KS.

A novel AlGaN/GaN based heterostructure field effect transistor (HFET) structure by employing the SiO_2 insulated-gate and the delta-doped barrier with very high breakdown voltage is reported. In general, the Schottky gate of AlGaN/GaN based HFETs tends to degrade with enhanced gate leakage current and insufficient pinch-off characteristics, especially operating under high power and high temperature conditions. The degradation of the gate leads to the premature breakdown and hence a deficient device performance with a reduction of output power, the RF efficiency and noise figure. To overcome these problems related with the Schottky gate, we have employed a novel structure by combining the insulate gate oxide and the delta-doped barrier layer to reduce the gate leakage and premature breakdown phenomena. The fabrication and DC characterization of the device are reported. The device has high drain current drive and gate control capabilities with a maximum saturation current of about 1.3 A/mm, a peak extrinsic transconductance around 180 mS/mm, and a high gate-drain breakdown voltage exceeding 200 V for 1 mm gate-drain distance. These characteristics indicate a great potential of this unique structure for high power microwave applications. The influence of doping level and doping scheme on the DC characterization and the breakdown voltage is also reported.

SESSION L10: CHARACTERIZATION OF DEFECTS AND TRANSPORT
Chair: Michael J. Manfra
Thursday Afternoon, December 5, 2002
Room 302 (Hynes)

1:30 PM *L10.1
ELECTRICAL AND OPTICAL PROPERTIES OF VERY PURE GaN. D.C. Look, Semiconductor Research Center, Wright State University, Dayton, OH; S.S. Park and J.H. Han, Samsung Advanced Institute of Technology, Suwon, KOREA.

For most semiconductor materials, donor energies determined by temperature-dependent Hall-effect (T-Hall) measurements are

significantly smaller than those measured by photoluminescence (PL) measurements, due to screening, inhomogeneity, inherent measurement and fitting inaccuracies, and other factors. In general, accurate comparisons are possible only in very pure materials. Here we discuss measurements in a 248-μm-thick GaN layer grown by hydride vapor-phase epitaxy and separated from its Al_2O_3 substrate. The fitting of T-Hall data produces the following parameters: $\mu(300)$ = 1320 cm^2/V-s; μ(peak) = 12,000 cm^2/V-s; n(300) = 6.27 x 10^{15} cm^{-3}; ND = 7.5 x 10^{15} cm^{-3}; and NA = 1.3 x 10^{15} cm^{-3}. As far as we know, $\mu(300)$ and μ(peak) are higher than any ever reported in GaN, and N_A, lower. The shallow donor N_D, likely due to oxygen, has a Hall activation energy of 27.7 meV. PL spectra show a strong donor-bound exciton (D^0X) line at 3.47225 eV, and a weaker one at 3.47305 eV. The normalized intensities of these two lines are quite well reproduced by a pair of n = 2 replicas, at 3.44686 and 3.44792 eV, giving E_D(n=2) E_D(n=1) = 24.5 and 25.1 meV, respectively, for the two donors. The GaN donor effective Rydberg R has recently been given as 29.1 meV [1], which means that EC ED(n=2) $\cong$ R/4 = 7.3 meV, since the n = 2 states should follow the hydrogenic model. The ground-state activation energies [E_C E_DD(n=1)] of the stronger and weaker donors are then 31.8 and 32.6 meV, respectively, clearly larger than the expected hydrogenic value of 29.1 meV. Note that the Hall energy, 27.7 meV, cannot be directly compared with the PL energy, 31.8 meV, because n = 2 and higher states should, in principle, be included in the Hall analysis. We discuss the effects of these excited states on the Hall/PL discrepancy, and on T-Hall fitting in general.
[1] W.J. Moore et al., Phys. Rev. B **65**, 081201 (2002).

2:00 PM L10.2
OBSERVATIONS OF ELECTRON VELOCITY OVERSHOOT DURING HIGH-FIELD TRANSPORT IN AlN. Ramon Collazo, Raoul Schlesser, Amy Roskowski, Robert F. Davis, Zlatko Sitar, North Carolina State Univ, Dept. of Materials Sci & Eng, Raleigh, NC.

The energy distribution of electrons transported through an intrinsic AlN film was directly measured as a function of the applied field. Following the transport, electrons were extracted into vacuum through a semitransparent Au electrode and their energy distribution was measured using an electron spectrometer. The electron energy distribution featured kinetic energies higher than that of completely thermalized electrons. Transport through 80 nm thick layers revealed the onset of quasi-ballistic transport. This was evidenced by symmetric energy distributions centered at energies above the conduction band minimum for fields greater than 530 kV/cm. Drifted Fermi-Dirac energy distributions were fitted to the measured energy distributions, with the energy scale referenced to the bottom of the AlN conduction band. The drift energy and the carrier temperature were obtained as fitting parameters. Overshoots as high as five times the saturation velocity were observed and a transient length of less than 80 nm was deduced. In addition, the velocity-field characteristic along with energy relaxation times in the order of 10^{-14} s for fields greater than 500 kV/cm were deduced from these observations. This is the first experimental demonstration of this kind of transport in AlN.

2:15 PM L10.3
CYCLOTRON RESONANCE ON HIGH MOBILITY 2DEGS IN AlGaN/GaN HETEROSTRUCTURES. S. Syed, Columbia Univ., New York, NY; M. Manfra, Bell Labs, Murray Hill, NJ; Y-J. Wang, NHMFL, Tallahassee, FL; R.J. Molnar, MIT, Cambridge, MA; H.L. Stormer, Columbia Univ., New York, NY and Bell Labs, Murray Hill, NJ; L.N. Pfeiffer, Bell Labs, Murray Hill, NJ; K.W. West, Bell Labs, Murray Hill, NJ.

We have carried out cyclotron resonance (CR) studies on high-mobility, two-dimensional electron gas (2DEG) systems at the interface of AlGaN and GaN. We determine masses, non-parabolicities, scattering times, and observe an unexpected splitting. The heterostructures are grown by plasma-assisted molecular beam epitaxy(MBE)on semi-insulating GaN templates prepared on sapphire [0001] substrates by means of hydride vapor phase epitaxy (HVPE). The HVPE templates are typically $\sim 20\mu m$ thick and are compensated by Zn doping to achieve room temperature resistivities of $\sim 10^8 \Omega cm$. The 2D channel density of the specimens range between $n_e = 1 - 4 \times 10^{12} cm^{-2}$ with mobilities ranging from $\sim 8,000$ to $\sim 30,000 cm^2/Vsec$. The wide range in density was achieved by systematically changing the Al-concentration in the barrier from 3 to 10%. Good electrical isolation between the 2D carriers and those in the HVPE template is attested to by carrier densities that remain unchanged from 1.7 to $\sim$ 100K and by low temperature magnetotransport measurements that show vanishing resistivities due to the Quantum Hall Effect. CR experiments were carried out at 4K using a Bruker Fourier transform spectrometer in combination with a Si-Ge composite bolometer. We have measured the effective mass, m^*, and the cyclotron resonance lifetime, τ_{CR}, of the 2DEG carriers as a function of electron density, n_e. We compare the variation of m^* with n_e observed in our experiments with theoretical predictions and contrast the values of τ_{CR} against the mobility and quantum scattering times obtained from low-temperature transport measurements. Moreover, we observe unexpected low-energy splittings in the CR of the 2DEG and discuss these data in light of splittings previously observed in other material systems.

2:30 PM L10.4
ELECTROREFLECTANCE STUDIES OF THE AlGaN/GaN HETEROSTRUCTURE AND 2-DIMENSIONAL ELECTRON GAS. S.R. Kurtz, A.A. Allerman, D.D. Koleske, and G.M. Peake, Sandia National Laboratories, Albuquerque, NM.

Large piezoelectric and spontaneous polarization fields occurring in AlGaN/GaN heterostructures can produce a 2-dimensional electron gas (2DEG) without doping. In this work, electronic properties of AlGaN/GaN heterostructures and field-effect transistors were determined using a contacted electroreflectance technique, and we show that electroreflectance augments conventional electrical characterization of GaN-based field-effect transistors. By studying variations in the electroreflectance with applied electric field, spectral features associated with the AlGaN barrier, the 2DEG at the interface, and bulk GaN are clearly identified. The 2DEG produced a broad, first-derivative-like electroreflectance feature. With bias voltage, the 2DEG electroreflectance narrowed and converged with the GaN band-edge. The 2DEG Fermi energy was determined from analysis of the line-shape. The AlGaN barrier displayed Franz-Keldysh oscillations which provided estimates of barrier-layer composition and electric field. The period of the Franz-Keldysh oscillations varied with bias voltage. Large discrepancies were observed between measured AlGaN barrier compositions and compositions projected from MOCVD growth calibrations. For heterostructures grown on sapphire, AlGaN electric fields determined from the Franz-Keldysh oscillations were anomalously larger than those predicted by AlGaN/GaN heterostructure models. Possible explanations for the large electric field values include electron trapping within the AlGaN barrier or an AlGaN composition gradient. The electroreflectance of AlGaN/GaN heterostructures grown under different conditions will be compared. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Dept. of Energy under contract DE-AC04-94AL85000.

3:15 PM L10.5
ORIGIN OF THE EFFICIENT LIGHT EMISSION AT INVERSION DOMAIN BOUNDARIES IN GaN. Vincenzo Fiorentini, INFM and Dipartimento di Fisica, Università di Cagliari, ITALY.

GaN is an efficient light emitter despite its relatively poor material quality. Polycrystallinity in the form of opposite polarity domains has been suggested not to adversely influence light emission, because inversion domain boundaries (IDB*) do not produce deep electronic levels [1]. Recently, as a corollary of intentional domain formation on patterned substrates for the demonstration of polarization effects, it was found that inversion domain boundaries luminesce one order of magnitude *more efficiently* than normal material [2]. I have undertaken first-principle density functional calculations with the projector augmented wave method and the VASP code. The bulk structure of GaN is described very accurately. The IDB* is simulated in a large orthorombic supercell. The defect causes no strain, and minor local relaxations. Its formation energy is quite low, 22 meV/Å^2. I find that the planar defect induces locally a "1D-mexican-hat" potential attracting both holes (with its central region) and electrons (with its wings), thus explaining the concurrent accumulation of electrons and holes near the defect. The explicit addition of a hole or an electron to the simulation cell confirm indeed the expected (weak) localization. Basically the effect is due to the local structure being distorted towards that of NaCl. In experiment, the emission is observed to be polarized in the IDB* plane. The bulk interband transition normally takes place between a twofold degenerate N–p_xp_y-like Γ_6 valence state and a N–s-like Γ_1 conduction state, leading to no preferred polarization. At the IDB* defect, instead, the top valence state is locally modified by an admixture of p_z character, so that the transition produces a partially in-plane polarized emission. The transition energies, calculated with the ΔSCF principle, are in close agreement with experiment both for the undefected bulk (3.49 eV) and the for defected system (3.44 eV, accounting for the very weak interdefect repulsion). In conclusion, the IDB* planar defect is an efficient shallow recombination center in GaN, whose properties are of purely electronic-structure origin.
[1] J.E. Northrup et al. Phys. Rev. Lett. **77**, 103 (1996)
[2] P.J. Schuck et al., Appl. Phys. Lett. **79**, 952 (2001)

3:30 PM L10.6
PHOTO-ELECTRON EMISSION MICROSCOPY (PEEM) OBSERVATION OF INVERSION DOMAIN BOUNDARIES OF GaN-BASED LATERAL POLARITY HETEROSTRUCTURES. Woochul Yang, B.J. Rodriguez, R.J. Nemanich, North Carolina State Univ., Dept of Physics, Raleigh, NC; O. Ambacher, Technical

University Ilmenau, Institute for Solid State Electronics Nanotechnology, Ilmenau, GERMANY.

A PIMBE grown GaN film with laterally patterned Ga- and N-face polarities was explored using in situ UV-photo-electron emission microscopy (PEEM). The photo-electrons were excited with UV-light from the tunable UV free electron laser (FEL) at Duke University. PEEM images were obtained with photon energies from 4.5 to 6.5 eV, and the surfaces were examined before and after in situ cleaning with exposure to a NH_3 flux at 800°C. Before CVC cleaning, the image contrast of the Ga- and N-face polarities regions was not significant. However, after cleaning the brightness contrast between different polarity regions of the surfaces was significantly enhanced, and the N-face regions were slightly brighter than the Ga-face regions. Moreover, bright emission was detected from the inversion domain boundaries (IDBs) at the leteral heterostructure. Surfaces were also examined with piezoresponse force microscopy (PFM), and it was evident that the contrasts of the IDB in the PEEM and PFM techniques were correlated. The photo-threshold of IDB measured by PEEM was about 4.8 eV. The polarity contrast and intense emission from IDBs of GaN film in PEEM are discussed in terms of the polarization fields and work function variation induced by bound surface charges.

3:45 PM L10.7
CONCENTRATION-DEPENDENT CARBON DOPING BEHAVIOR IN MBE-GROWN GaN AND ITS INFLUENCE ON ELECTRICAL AND OPTICAL PROPERTIES. Rob Armitage, Qing Yang, Henning Feick, Jonathan Lim, Eicke R. Weber, Dept of Materials Science and Engineering, University of California, Berkeley, and Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA.

Understanding the influence of carbon-related defects in GaN is important because significant levels of carbon contamination are introduced in growth processes using metalorganic gallium precursors such as MOVPE. The present study involves GaN epilayers grown by plasma-assisted molecular-beam epitaxy on MOVPE-GaN/sapphire templates and intentionally doped with carbon using a carbon tetrachloride vapor source. The range of carbon concentrations investigated is 5×10^{16} to 5×10^{20} cm^{-3}. For moderate doping, semi-insulating GaN is obtained when the carbon concentration exceeds the residual donor concentration. However, p-type conductivity is not observed for any concentration because the tendency for carbon atoms to incorporate as acceptors diminishes dramatically with increasing doping level. Very heavily carbon-doped show high n-type conductivity, indicating that a simple Fermi level dependence of the carbon defect formation energy cannot explain the concentration-dependent doping behavior. Photoluminescence measurements show two broad bands centered at 2.2 eV (yellow) and 2.9 eV (blue). The relative intensities of both bands increase with carbon concentration, but the yellow band dominates in n-type samples. The results are discussed in terms of the several different types of carbon point defects expected to exist in GaN, and a qualitative model is proposed to explain the concentration dependence of the doping behavior.

4:00 PM L10.8
QUANTITATIVE DETERMINATION OF THE KINETICS OF NANOPIPE GROWTH IN GaN. E.A. Stach, National Center for Electron Microscopy, Lawrence Berkeley National Laboratory, Berkeley, CA; W.S. Wong and M. Kneissl, Palo Alto Research Center, Palo Alto, CA.

Frank proposed in 1951 that if a dislocation has a sufficiently large Burgers vector, a state of equilibrium should exist in which the core of the dislocation is empty (Frank, Acta Cryst., 1951). Empty core dislocations also known as micropipes or nanopipes have been observed in both SiC and GaN materials, and are associated with non-ideal electronic behavior. Questions remain, however, concerning the mechanism of their formation. In particular, it has been observed that the diameter of the pipes in these systems often far exceeds that predicted by Franks equilibrium theory. Additionally, it has been known for some time that at temperatures in excess of about 850°C nitrogen will spontaneously desorb from GaN. We have utilized in-situ transmission electron microscopy to quantitatively determine the rate of nitrogen desorption from GaN at temperatures from 850°C to 1050°C at vacuum levels on the order 1×10^{-7} torr. This was done using high magnification diffraction contrast images from electron transparent, freestanding GaN films produced by the laser lift-off method. The thickness of the GaN crystals was determined using two-beam convergent beam electron diffraction patterns, and the volume was determined by quantitative imaging processing, correlated with prior knowledge of two-beam electron extinction distances in GaN. The activation energy of desorption was determined at the edge of the bulk crystal, at the location of pre-existing nanopipes, and along the cores of pre-existing screw, edge and mixed dislocations. Generally, desorption from the bulk crystal proceeds along the $\{10\bar{1}0\}$ prism planes and results in strong hexagonal faceting. In the case of pre-existing nanopipes, desorption proceeds relatively uniformly from the $\{10\bar{1}0\}$ planes that define the pipe boundary. The average diameter of the pipe increases with time at temperature, but the activation energy of desorption is slightly higher than that observed from the bulk. At higher temperatures (on the order of 950°C) pre-existing screw dislocations begin to empty out, while in the case of mixed and edge dislocations, nanopipe formation does not occur, even when annealing temperatures exceed 1150°C. This is consistent with their smaller Burgers vector in comparison with pure screw dislocations. These results indicate that the nitrogen desorption is the primary formation mechanism of nanopipes in GaN. The reason that they obtain sizes larger than predicted by equilibrium theory is directly related to the kinetics of nitrogen desorption from pre-existing $\{10\bar{1}0\}$ faces of the nanopipes.

4:15 PM L10.9
HOLLOW-CORE DISLOCATIONS IN Mg-DOPED AlGaN. David Cherns, Marcus Q. Baines, Suman-Lata Sahonta, Yiqian Wang, Bristol Univ, Dept of Physics, Bristol, UNITED KINGDOM; Rong Liu, Fernando A. Ponce, Arizona State Univ, Dept of Physics, Tempe, AZ; Hiroshi Amano, Isamu Akasaki, Dept of Mat. Sci and Eng, Meijo Univ, Nagoya, JAPAN.

The issue of whether dislocations in GaN are open or closed core is of great interest for understanding their electrical properties. It is well established that c-type (screw) dislocations are often open core with diameters of typically 5-25nm i.e. nanopipes. In contrast, there is little evidence that a-type (edge) or c+a-type (mixed) dislocations, which usually predominate in device structures, have open core configurations. In this paper we report, for the first time, open core dislocations of both edge and mixed type. Studies were carried out on Mg-doped (10^{20} cm^{-3}) $Al_{0.03}Ga_{0.97}N$ films grown by MOCVD on (0001) sapphire. Transmission electron microscopy studies were carried out on plan view and cross-sectional samples. Studies on cross-sections showed that the films contained inverted hexagonal pyramids indicative of local Mg precipitation. Such precipitation was, however, non-isotropic, with denuded regions around threading edge and mixed dislocations contrasting with enhanced precipitation much closer to the cores. Close inspection suggested that the dislocations had hollow cores with diameters of typically 1-2nm, although varying periodically along their length in some cases. This was confirmed by studies of plan-view samples, where the open cores were clearly visible in the end-on orientation. The results strongly imply that nanopipe formation is correlated with the segregation of Mg to the dislocation cores. The paper will describe the core structures generated and propose a mechanism for their formation. The wider implications for understanding the electrical properties of p-doped GaN structures will also be discussed.

4:30 PM L10.10
DEVELOPMENT OF A HIGH-RESOLUTION ELECTRON BEAM INDUCED CURRENT TECHNIQUE FOR ELECTRICAL CHARACTERIZATION OF InGaN-BASED QUANTUM WELL LIGHT EMITTING DIODES. K.L. Bunker, J.C. Gonzalez, A.D. Batchelor, P.E. Russell, Materials Science and Engineering Department, North Carolina State University, Raleigh, NC; T.J. Stark, Materials Analytical Services, Raleigh, NC.

Electron Beam Induced Current (EBIC) experiments using a Scanning Transmission Electron Microscope (STEM) were used to determine the p-n junction location of an InGaN quantum well (QW) Light Emitting Diode (LED) with respect to the QW position. The conventional "H-bar" Transmission Electron Microscopy (TEM) sample preparation method using Focused Ion Beam Micromachining (FIBM) was adapted to create an electron-transparent membrane approximately 300 nm thick on the sample while preserving the electrical activity of the device. A STEM-EBIC sample holder with two insulated electrical feedthroughs making contact to the thinned LED was designed and custom made for these experiments. The external electronic acquisition system included a Keithley 614 current amplifier connected to a second low gain voltage amplifier specifically for signal inversion. The positive voltage signal was converted to a frequency using a Voltage to Frequency Converter (VFC) and sent to one of the Multichannel Scaler (MCS) ports of the Thermo Noran Vantage Energy Dispersive Spectroscopy (EDS) system. This setup allowed for simultaneous acquisition of large angle scattered electrons (i.e. Z-contrast), EBIC, and EDS images. STEM-EBIC experiments were performed in the linescan configuration (i.e. the electron beam scans the surface perpendicular to the depletion layer of the device) in a Hitachi HD-2000 STEM. The combination of a high beam energy (200 keV) and an electron transparent sample (300 nm) used in the STEM allows for nanometer spatial resolution during EBIC experiments. Due to the high injection conditions used in the experiments, no information about electrical transport of the minority carriers, such as the minority carrier diffusion length, was obtained. However, the position of the p-n junction, defined in these

experiments as the position of the maximum built-in electric field in the sample, was resolved with nanometer precision. The simultaneous collection of Z-contrast images, EBIC images, and In and Al elemental images allowed for the determination of the p-n junction location, AlGaN and GaN barrier layers, and thin InGaN quantum well layer within the device. The relative position of the p-n junction with respect to the thin InGaN quantum well was found to be (19 ± 3) nm from the center of the InGaN quantum well.

4:45 PM L10.11
BANDGAP EVOLUTION, HYBRIDIZATION AND THERMAL STABILITY OF $In_xGa_{1-x}N$ ALLOYS MEASURED BY SOFT X-RAY EMISSION AND ABSORPTION. Cormac McGuinness, Philip Ryan, James E. Downes, Kevin E. Smith, Boston University, Physics Dept., Boston, MA; Dharanipal Doppalapudi, Theodore D. Moustakas, Boston University, Electrical and Computer Engineering Department, Boston, MA.

The electronic structure of $In_xGa_{1-x}N$ alloys with $0 \leq x \leq 0.3$ has been studied using synchrotron radiation excited soft x-ray emission and absorption spectroscopies. These spectroscopies allow the elementally resolved partial densities of states of both the valence and conduction bands to be measured. The x-ray absorption measurements indicate that the conduction band broadens considerably with increasing indium incorporation. The evolution of the band gap as a function of indium content derives primarily from this broadening of the conduction band states. The x-ray emission spectra indicate that motion of the valence band akes a smaller contribution to the evolution of the band gap. This gap evolution differs from previous studies of the $Al_xGa_{1-x}N$ alloy system, which observed a linear valence band shift through the series $0 \leq x \leq 1$. For $In_xGa_{1-x}N$, the valence band exhibits a large shift between x=0.0 and x=0.1 with it being static thereafter. We also report evidence of In 4*d*-N 2*p* and Ga 3*d*-N 2*p* hybridization. Finally the thermal stability of an $In_{0.11}Ga_{0.89}N$ film was investigated. Both emission and absorption spectra were found to have a temperature dependent shift in energy, but the overall definition of the spectra was unaltered even at annealing temperatures well above the growth temperature of the film. This work was supported in part by the National Science Foundation under grant number DMR-99-86099 and the U.S. Army Research Office under grant 40126-PH. Our x-ray emission spectrometer is funded by the US Army Research Office under DAAH04-95-0014. Experiments were performed at the NSLS which is supported by the U.S. Department of Energy, Divisions of Materials and Chemical Sciences. T.D.M. acknowledges the support of DoD/ARPA under grant MDA972-96-3-0014.

SESSION L11: POSTER SESSION
Thursday Evening, December 5, 2002
8:00 PM
Exhibition Hall D (Hynes)

L11.1
BLUE LUMINESCENCE IN UNDOPED AND Zn-DOPED GaN. M.A. Reshchikov, H. Morkoç, Dept. of Electrical Engineering, VCU, Richmond, VA; R.J. Molnar, MIT Lincoln Laboratory, Lexington, MA; D. Tsvetkov and V. Dmitriev, TDI, Inc., Silver Spring, MD.

A broad band with a maximum at about 2.9 eV (blue band) is widely observed in the photoluminescence (PL) and cathodoluminescence (CL) spectra of unintentionally doped GaN grown by metalorganic vapor phase epitaxy (MOVPE) or by hydride vapor phase epitaxy (HVPE). In some samples this band exhibits fine structure attributed to electron-phonon coupling, in others it appears featureless. Different defect origin and recombination mechanisms responsible for the blue band have been suggested in the past. The situation is complicated by the fact that bands similar in shape and position were observed also in Zn- and Mg-doped GaN, as well as in undoped GaN after dry or wet etching. We investigated PL in HVPE-grown undoped and Zn-doped GaN layers in wide temperature and excitation intensity ranges. We have found that the shape, temperature and excitation intensity dependencies of the blue band in undoped GaN are almost identical to those in GaN lightly doped with Zn. Moreover, in both undoped and Zn-doped samples we observed a distinctive set of peaks related to an exciton bound to the Zn acceptor. A detailed study of behavior of the blue band in Mg-doped GaN and undoped GaN subjected to wet chemical etching revealed dissimilarities from that in undoped and Zn-doped GaN. Although the exact structure of the Zn acceptor is still unknown, our experimental results unambiguously demonstrate that Zn impurity is responsible for the blue band in unintentionally doped GaN.

L11.2
SURFACE-RELATED PHOTOLUMINESCENCE EFFECTS IN GaN. M.A. Reshchikov, D. Huang, M. Zafar Iqbal, L. He, and H. Morkoç, Dept. of Electrical Engineering, Virginia Commonwealth University, Richmond, VA.

Photoluminescence (PL) from GaN epilayers is found to be sensitive to the surface conditions and to the ambient atmosphere during measurement. We studied the effect of UV illumination in different ambients including air, oxygen, nitrogen and hydrogen gases on room-temperature PL of GaN grown on sapphire by molecular beam epitaxy. In some samples the luminescence intensity increased markedly in vacuum as compared to excitation in air, whereas in others it decreased appreciably. While air and oxygen showed strong reversible variation of PL intensity as compared to vacuum, nitrogen and hydrogen atmospheres led to a very small change. In some samples we observed shift of the yellow luminescence band with change of ambient, in others no shift was detected. Most of the results can be explained by variation of the band bending near the surface caused by effect of UV illumination and/or different ambients on the surface states. The surface-related PL effects will be correlated with the growth conditions, surface morphology and polarity of GaN.

L11.3
EXCITONS BOUND TO SURFACE DEFECTS IN GaN. M.A. Reshchikov, D. Huang, and H. Morkoç, Dept. of Electrical Engineering, Virginia Commonwealth University, Richmond, VA.

Sharp intense peaks are sometimes detected in the low-temperature photoluminescence (PL) spectrum of undoped GaN samples in the photon energy range of 3.0 - 3.45 eV. Some of these peaks can be attributed to excitons bound to dislocations and inversion domains, whereas some others originate from the GaN surface because they can be affected essentially by surface treatment. In our samples, grown by molecular beam epitaxy on sapphire substrate, the 3.41 eV peak always disappeared after removing the surface layer by etching for a few seconds in hot phosphoric acid. Atomic force microscopy (AFM) images confirmed that such light etching modifies the surface morphology, although the etched depth is negligibly small. Intensities of two other peaks (at 3.30 and 3.36 eV) also depended on the sample etching, as well as on time of subsequent exposure to air. The 3.30 and 3.36 eV peaks evolved with time of UV illumination, increasing by several times and demonstrating memory effect at low temperature. A set of LO phonon replicas has been observed for the 3.30 and 3.41 eV peaks. The 3.36 eV peak appeared only in the samples with relatively strong 3.30 and 3.20 eV peaks and its phonon replicas could not be observed. Small values of the Huang-Rhys factor, as well as slow quenching of PL intensity with temperature favors attribution of these peaks to bound excitons. The presence of the surface-related PL peaks will be correlated with the growth conditions, surface morphology and polarity of GaN.

L11.4
TUNNEL EFFECTS IN LUMINESCENCE SPECTRA OF GaN-BASED HETEROSTRUCTURES. A.E. Yunovich, V.E. Kudryashov, A.N. Turkin, Dept of Physics, M.V. Lomonosov Moscow State University, Moscow, RUSSIA; M. Leroux, S. Dalmasso, CRHEA-CNRS, Valbonne, FRANCE.

Tunnel effects in luminescence spectra and electrical properties of GaN- LEDs were studied. The heterostructures of the LEDs were grown by MOCVD- technique in various laboratories (Nichia, Hewlett Packard, CRHEA-CNRS, UniRoyal). The tunnel radiation predominates at low currents (J<0.2 mA) in a wide spectral range of 1.9-2.7 eV. This range is greater than in our first publication on the subject (2.1-2.4 eV) [1]; see also [2]. The position of the tunnel maximum hwmax is equal to the applied voltage eU. Earlier this phenomena was theoretically analyzed for cubic $A^{III}B^{V}$ compounds [3, 4]. The spectral band is described by this theory and the long wavelength tail of the spectra is described by an exponential parameter of the Franz-Keldysh effect dependent on the reduced effective mass m_{cv} and the electric field E. Energy diagram of GaN-based heterostructures is analyzed. Tunnel recombination mechanisms are more probable if the electric fields in the quantum well InGaN-layer, created by piezoelectric effect, is directed in the direction opposite to the field of the p-n- junction. The electric field in the active layer evaluated from fitting of experimental spectra is of the order E = 0.5 - 1.5 10^6 V/cm. The tunnel spectral band was not detected in the LEDs with a high radiation efficiency in the main spectral band. 1. A.E. Yunovich, A.N. Kovalev, V.E. Kudryashov, F.I. Manyachin, A.N. Turkin, K.G. Zolina. Tunnel effects in luminescence spectra of InGaN/AlGaN/GaN light-emitting diodes. Mat. Res. Soc. Symp. Proc. Vol. 449, 1997, p.1167-1172. 2. N. Grandjean, B. Damilano, S. Dalmasso, M. Leroux, Marguerite Laugt, and J. Massies, J. Appl. Phys., 86, 3714 (1999). 3. A.E. Yunovich, A.B. Ormont. ZhETP, 1966, v. 51, N 11, pp.1292-1305. 4. T.N. Morgan. Phys. Rev., 1966, Vol. 148, N 2, pp.890-903.

L11.5
SELF-INDUCED PHOTON ABSORPTION BY SCREENING OF

ELECTRIC FIELDS IN NITRIDE BASED QUANTUM WELLS. Sokratis Kalliakos, Pierre Lefebvre, Thierry Taliercio, Bernard Gil, CNRS, Universite Montpellier II, FRANCE.

We have calculated the change of interband absorption spectra of a variety of quantum wells based on hexagonal group-III nitride semiconductors, under photo-injection of high densities of electron-hole pairs. The screening of internal electric fields by such optical excitation is known to blue-shift and reinforce the ground-state optical transition. Due to large values of densities of states and of internal fields, we predict novel properties that rather concern optical absorption via transitions between excited states. The absorption coefficient can be strongly enhanced by the optical excitation itself, in this particular spectral region, yielding the possibility for self-induced absorption properties. In other words, if sufficiently intense, an excitation laser can increase the absorption coefficient of the system at its own wavelength, thus providing a strongly nonlinear optical response. We discuss quantitatively the possible applications of these original properties to tunable optical limitation, and we propose a detailed study of their time-dependent aspects.

L11.6
TIME-RESOLVED OPTICAL STUDIES OF InGaN LAYERS GROWN ON LGO SUBSTRATES. Maurice Cheung, Fei Chen, Madalina Furis, A.N. Cartwright, University at Buffalo, State University of New York, Buffalo, NY; Gon Namkoong, W. Alan Doolittle, Georgia Institute of Technology, Atlanta, GA; April Brown, Duke University, Durham, NC.

Radiative recombination processes in InGaN bulk and p-i(multiple quantum well)-n structures grown by molecular beam epitaxy (MBE) on lithium gallate (LGO) substrates were investigated using intensity and temperature dependent time-resolved and CW photoluminescence. The improved structural quality resulting from the improved lattice match of LGO to III-Nitrides simplifies these investigations because well-defined composition phases can be analyzed for both homogeneous and phase separated InGaN samples. Epilayers of InGaN intentionally grown with and without indium segregation were studied using time-resolved photoluminescence (PL) and x-ray techniques. X-ray diffraction measurements showed that the homogeneous epilayer was high quality $In_{0.208}Ga_{0.702}N$ and the segregated epilayer exhibited peaks corresponding to both $In_{0.289}Ga_{0.711}N$ and $In_{0.443}Ga_{0.557}N$. Consistent with recent literature attributing improved luminescence properties to indium segregation, the PL lifetime of the segregated epilayer was about three times that of the homogeneous sample. Moreover, the segregated sample exhibited a three times larger red shift immediately after femtosecond pulsed excitation than the homogeneous sample. Finally, p-i-n MQW InGaN/GaN structures grown on LGO, with similar intrinsic regions grown on p-doped and n-doped GaN bulk layers respectively, were intentionally designed with the in-well piezoelectric field either in the same direction or the opposite direction of the p-i-n field. These two structures showed very different emission spectra; the p-i-n grown on n-doped bulk exhibited only a broad emission centered at 3.30 eV, a strong signature of the Mg-doping in the p-doped epilayer, while the structure grown on p-doped bulk exhibited a narrow excitonic emission feature at 3.25 eV. This 3.25 eV excitonic emission feature does not shift with time after pulsed excitation implying in-well piezoelectric field has been reduced (estimated to be < 300 kV/cm) by the built-in p-i-n field.

L11.7
Abstract Withdrawn.

L11.8
FEMTOSECOND PUMP AND PROBE SPECTROSCOPY OF OPTICAL NONLINEARITIES IN InGaN/GaN HETERO-STRUCTURES. Fei Chen, M.C. Cheung, Paul M. Sweeney, W.D. Kirkey, M. Furis, A.N. Cartwright, Department of Electrical Engineering, University at Buffalo, Buffalo, NY.

Femtosecond pump-probe spectroscopy is used to obtain additional physical insight on carrier transport and recombination dynamics in InGaN heterostructures by separating field screening behavior from excitonic phase space filling effects. Although nitride based semiconductors have been successfully used in the commercial products for high brightness light-emitting diodes from UV to amber there is still a lack of understanding of the complex carrier dynamics that exist within these materials. Traditional CW photoluminescence (PL) and time resolved PL measure only the radiative recombination dynamics. In this paper, the transition of the differential absorption spectral signature from the signature for excitonic bleaching to the signature for an excitonic blue shift as the carrier injection was reduced is reported for the first time in InGaN/GaN multiple quantum wells (MQWs). The single color pump and the white-light probe were derived from an amplified 250kHz Ti:Sapphire laser system to inject sufficiently high carrier densities to observe both optical nonlinearities. For high excitation intensity the spectral features indicate that the effects of band filling of the localized states and excitonic quenching (bleaching) dominate, while for low excitation intensity the spectral response is typical of an excitonic blue shift signature due to field screening through the quantum-confined Stark effect (QCSE). Moreover, the in-well piezoelectric field estimated at the transition point between the two signatures, is consistent with the calculated value resulting from piezoelectric polarization in this particular $In_{0.1}Ga_{0.9}N$ strained well. The temporal resolution indicates that the photoinduced carriers initially drift in the well under the piezoelectric field and screen the in-well field until the bands become flat. Any remaining excess carriers fill localized states once flat-band conditions are reached. Once all localized states are filled and internal fields are screened, carriers begin to quench the excitonic transition through excitonic screening and/or phase space filling.

L11.9
RELATION BETWEEN STRUCTURAL AND OPTICAL PROPERTIES OF InGaN HETEROSTRUCTURES CLOSE TO THE CRITICAL LAYER THICKNESS: THE INFLUENCE OF STRAIN ON THE EMISSION ENERGIES. S. Pereira, M.R. Correia, E. Pereira, Departamento de Física, Universidade de Aveiro, PORTUGAL; K.P. O'Donnell, C. Trager-Cowan, F. Sweeney, Department of Physics, University of Strathclyde, Glasgow, UNITED KINGDOM.

Structural and optical properties of In(x)Ga(1-x)N attract enormous interest because of recent advances in visible light-emitting devices based on this semiconductor alloy. One of the topics under continuing debate in the III-nitride community, is the formation of "quantum dot-like In-rich regions" in InGaN. Frequently, researchers ascribe the appearance of InGaN-related double luminescence peaks (DLP) to a spontaneous formation of such nanometer-sized regions. In this contribution, we present a systematic multidisciplinary study which shows that DLP are *not* evidential of phase segregation and may instead be ascribed with confidence to a nearly discontinuous strain relaxation (DSR), previously identified in InGaN by Pereira *et al* [1]. To gain an overview of this issue, we first calculated the values of critical layer thickness (CLT) as a function of composition using the model proposed by People and Bean [2]. Subsequently, the occurrence of DSR when CLT(x) is exceeded is revealed for various layers with different compositions (x) and thicknesses (t) by high-resolution X-ray diffraction (XRD). Additionally, surface profiling analysis by atomic force microscopy shows that layers with $t >$ CLT(x) have a 3D surface morphology characterised by a large microscopic roughness. Next, we demonstrate that the DSR accounts for the emergence of a second, lower energy, luminescence peak. The two components of the samples luminescence, originating in regions of different strain, can be distinguished by depth resolved cathodoluminescence spectroscopy. A literature survey also shows that most reported DLPs may indeed be explained by the presence of DSR after the CLT. The energy splitting of the two luminescence components: $\Delta E=0.305*E-1.077$(r=0.99), tends to zero near the GaN band edge. A simple model to predict the energy separation will be presented. [1] S. Pereira *et al*, Appl. Phys. Lett. 79, 1432 (2001). [2] R. People and J.C. Bean, Appl. Phys. Lett. 47, 322 (1985).

L11.10
UNUSUAL TEMPERATURE DEPENDENCE OF THE PHOTOLUMINESCENCE PEAK ENERGY AND LINEWIDTH IN InGaN/GaN QUANTUM WELLS. R. Pecharroman-Gallego, R.W. Martin, Dept. of Physics, University of Strathclyde, Glasgow, Scotland, UNITED KINGDOM; I.M. Watson, Institute of Photonics, University of Strathclyde, Glasgow, Scotland, UNITED KINGDOM.

An analysis of photoluminescence spectra for a range of single and multiple InGaN/GaN quantum wells as a function of temperature is presented. The well-known anomalous "S-Shape" behaviour [e. g. 1 3] is observed for samples emitting over a very wide range of energies, with PL peak emission energies ranging from approximately 1.8 eV (red) to 3.2 eV (violet) [4]. The PL peak energy blueshifts with temperature, in the region 40 200 K. The magnitude and temperature range of the blueshift are carefully analysed for a range of InGaN quantum wells as a function of the emission energy and number of wells. Furthermore the linewidth dependence of the PL peak in the region of the "S-shape" also showed an unusual behaviour; in some cases decreasing with temperature over the range in which the PL peak emission energy increases. We relate this behaviour to the delocalisation of the excitons and consider the importance of the temperature dependence of non-radiative processes and carrier lifetime. 1.- Petr G. Eliseev, Piotr Perlin, Jinhyun Lee and Marek Osinski. Appl. Phys. Lett. 71 (5) 569 (1997) 2.- Yong-Hoon Cho, G. H. Gainer, A. J. Fischer, J. J. Song, S. Keller, U. K. Mishra and S. P. DenBaars. Appl. Phys. Lett. 73 (10) 1370 (1998) 3.- K. L. Teo, J. S. Colton, P. Y. Yu, E. R. Weber, M. F. Li, W. Liu, K. Uchida, H. Tokunaga, N. Akatsu and K. Matsumoto. Appl. Phys. Lett. 73 (12) 1697 (1998) 4.- R. W. Martin, P. R. Edwards, R.

Pecharroman-Gallego, C. Lui, C. J. Deatcher, I. M. Watson and K. P. ODonnell. J. Phys. D: Appl. Phys. 35 604-608 (2002)

L11.11
EXCITONS OF THE STRUCTURE IN ZINC-BLENDE $In_xGa_{1-x}N$ AND THEIR PROPERTIES. Dimiter Alexandrov, Department of Electrical Engineering, Lakehead University, Thunder Bay, Ontario, CANADA.

The existence of newfound quasi-particles - excitons of the structure - having significant influence over properties of zinc-blende $In_xGa_{1-x}N$ is reported in this paper. The exciton of the structure is found during the authors investigation of unusual spectral shift [1, 2, 3] in quantum well structures on $In_xGa_{1-x}N$. The LCAO electron band structure of zinc-blende $In_xGa_{1-x}N$ is determined. New mathematical approach for calculation of energy sub-bands belonging to primitive super-cell of multinary compound alloy is introduced and applied. The approach takes into consideration that the electron energy depends on both electron wave vector and structure of the multinary compound alloy. The electron band structure of zinc-blende $In_xGa_{1-x}N$ is found as dependence on both the electron wave vector and the electron radius-vector. Existence of new type of exciton called exciton of the structure is found. The binding energy and the hydrogen like energy levels of the exciton of the structure are determined as functions of the structure of zinc-blende $In_xGa_{1-x}N$. It is found that the excitons of the structure have long lifetime and that the photon-stimulated emission has important place in interaction between them and optical radiation. It is proved that the excitons of the structure are localized quasi-particles. It is found that destroying of the excitons of the structure has place in their interactions with hetero-junction and these results are used as basis for explanation of the observed spectral shift in quantum well structures on zinc-blende $In_xGa_{1-x}N$. [1] S. Chichibu, T. Azuhata, T. Sota, S. Nakamura, Appl. Phys. Lett., 69, 4188 (1996); [2] P. Eliseev, P. Perlin, J. Lee, M. Osinski, Appl. Phys. Lett., 71, 569 (1997); [3] Y. Narukawa, Y. Kawakami, M. Funato, S. Fujita, Sh. Fujita, S. Nakamura, Appl. Phys. Lett., 70, 981 (1997).

L11.12
SIMULTANEOUS TEM AND CATHODOLUMINESCENCE IMAGING OF NON UNIFORMITY IN InGaN QUANTUM WELLS. N.M. Boyall, K. Durose, Dept of Physics, University of Durham, UNITED KINGDOM; C. Liu, I.M. Watson, Institute of Photonics, University of Strathclyde, UNITED KINGDOM.

Inhomogeneity of InGaN quantum wells is generally accepted to influence luminescence in nitride based light emitting structures. Here this phenomena is investigated directly using transmission electron microscopy (TEM) and cathodoluminescence (CL) techniques combined in one instrument. This is a JEOL 200CX TEM fitted with an Oxford Instruments MONO-CL system. This comprises a parabolic light collector inserted between the specimen and the objective polepiece. The luminescence is analysed and collected by a grating monochromator and a cooled PMT. This allows spectra to be analysed and both panchromatic and monochromatic imaging to be undertaken using the scanning TEM (STEM) mode of the TEM. InGaN quantum wells having In content ranging from 9% to 20.7% and 1, 2, 3, or 8 periods were grown by MOVPE. Panchromatic imaging revealed luminescence hot spots on the scale of $\sim 0.7\mu m$. These were irregularly distributed along the length of the wells. Modelling of the CL emission was used to normalise the intensity of the images to eliminate the effects of variations in foil thickness. Hence the hot spots were shown to be a property of the material and not an artefact of the specimens. The possible effects of variations in the well thickness and In concentration along the length of the wells was investigated by monochromatic CL imaging. Images were recorded both at the peak well emission wavelengths and nearby, hence enabling local variations to be probed. The origins of this long-range non-uniformity in the luminescence shall be discussed.

L11.13
AN IN-SITU TEM-CATHODOLUMINESCENCE STUDY OF ELECTRON BEAM DEGRADATION OF LUMINESCENCE FROM GaN AND InGaN QUANTUM WELLS. N.M. Boyall, K. Durose, Department of Physics, University of Durham, UNITED KINGDOM; I.M. Watson, Institute of Photonics, University of Strathclyde, UNITED KINGDOM.

InGaN/GaN multi-quantum wells were grown by MOVPE on sapphire (0001) substrates. Growth was initiated using a thin low-temperature nucleation layer, which was followed by an undoped GaN buffer. The InGaN quantum wells were nominally 2.5nm thick with GaN barriers of approximately 7nm. The quantum well structures were tuned to emit at 410nm at low temperatures. Cross section electron transparent specimens of the material were analysed in a JEOL 200CX transmission electron microscope (TEM) adapted to allow the collection of cathodoluminescence (CL) by the insertion of a parabolic mirror into the microscope above the specimen. This apparatus allows combined optoelectronic and microstructural properties to be investigated through the simultaneous collection of CL and transmitted electrons. The mirror plus spectrometer allows CL spectra to be recorded. CL imaging can then be done in scanning TEM (STEM) mode using either the panchromatic or monochromatic CL signals. CL spectra of the samples show a dominant peak at 360nm (from the GaN) together with a well defined peak at 410nm due to the quantum well. Prolonged examination in STEM mode caused slow degradation of the luminescence intensity. This was considerably accelerated by continuous electron beam irradiation during normal TEM imaging. A study of this degradation is presented. Decay of both the GaN and InGaN luminescence curves were monitored independently using the spectrometer, and was considerably faster in the quantum wells. This decay is analysed here using simple kinetic models. A mechanism for the process is postulated by analogy with the accepted model of electron beam degradation for halides and chalcogenides. This model is consistent with the published outcomes of photoluminescence studies of degradation in nitrides. Practical TEM-CL imaging regimes that minimise electron beam degradation are specified.

L11.14
ROOM-TEMPERATURE TIME-RESOLVED PHOTO-LUMINESCENCE OF UV EMISSION FROM GaN/AlN QUANTUM WELLS. Madalina Furis, Fei Chen, A.N. Cartwright, Dept of Electrical Engineering, University at Buffalo-State University of New York, Buffalo, NY; Hong Wu, William J. Schaff, Dept of Electrical Engineering, Cornell University, Ithaca, NY.

We report room temperature time-resolved photoluminescence (TRPL) studies of multiple quantum well (MQW) structures of heterostructures of the binaries GaN and AlN grown by molecular beam epitaxy. The eventual application of these structures is for GaN intersubband IR light emitters. However, as an initial study, the structures are evaluated at UV to correlate materials parameters relevant to IR light emission. The nominally 1nm GaN quantum wells are clad by 6nm of AlN on top of a thick AlN buffer grown on sapphire. The sample consisted of 20 quantum wells in each structure. The observed energy (around 3.7eV for all samples) of the peak of the emission spectrum is in excellent agreement with a model that includes the strong confinement present in these structures and the existence of the large built-in piezoelectric field and spontaneous polarization present inside the wells. Moreover, the observed lifetimes were energy dependent as should be expected from field dependent elongation of lifetimes due to spatial separation of the injected carriers. Specifically, the decay time at high energies can be fitted by a stretched exponential with a beta value of 0.8 which is consistent with carrier spatial separation. The lifetimes obtained from the fitting are of the order of 1ns, longer than the reported recombination lifetimes in similar GaN/AlGaN MQWs. On the low energy side of the PL feature the intensity time decay becomes exponential with lifetimes ranging from 3 to 5ns. Furthermore, consistent with screening of the in-well field as carriers are injected in the well, a clear blue shift of the emission is observed at short times. Subsequently, as the carriers recombine, the peak emission red-shifts and the screening of the field is reduced. The strong UV emission at room temperature makes these structures promising for UV emitters.

L11.15
OPTICAL PROPERTIES OF AlN/GaN SUPERLATTICES GROWN BY METALORGANIC VAPOR PHASE EPITAXY. Vanya Darakchieva, Plamen P. Paskov, IFM, Linköping University, SWEDEN; Mathias Schubert, Universität Leipzig, GERMANY; Tanya Paskova, Bo Monemar, IFM, Linköping University, SWEDEN; Satoshi Kamiyama, M. Iwaya, Hiroshi Amano, Isamu Akasaki, Dept of Electrical and Electronic Engeneering, Meijo University, JAPAN.

AlGaN/GaN heterostructures have recently attracted considerable attention due to their potential applications for high power transistors and ultraviolet laser diodes. Short period AlGaN/GaN or AlN/GaN superlattices (SLs) are very attractive for strain management, dislocation reduction, p-contacts and also infrared intersubband detectors. In this work we report on the optical properties of AlN/GaN SLs grown by metalorganic vapor phase epitaxy on (0001) sapphire substrates. The structures consist of 10 period SLs with different well thickness, keeping the well-barrier thickness ratio as 3:1. Undoped, Si-doped and Mg-doped SLs were studied by room temperature spectroscopic ellipsometry (SE) and low-temperature photoluminescence (PL) and cathodoluminescence (CL). The SE data are analyzed using a best-fit model lineshape calculation of the dielectric function and the two lowest direct band-to-band transitions of the SLs are determined. A distinct blue shift was found with decreasing well thickness, accompanied by a clear increase of the transition strength. The same trend is deduced from the PL and CL spectra where a broadening of the emission band with the increase of the SL period is also observed. The comparison between SE and PL spectra evidences a significant Stokes shift (> 400 meV) of the

emission in thicker structures implying a huge internal electric field in these SLs. The Si-doped structures exhibit a small blue shift of the emission, probably due to a partial screening of the internal field. The effect is more pronounced in the long-period SLs. The Mg-doping is found to result only in a broadening of the emission band.

L11.16
PECULIARITIES OF OPTICAL PROPERTIES OF GaN/AlGaN QUANTUM WELLS WITH INVERSION DOMAINS.
Maria Tkachman, Shubina Tatiana, Jmerik Valentin, Ratnikov Valentin, Ivanov Sergey, Ioffe Physico-Technical Inst, St. Petersburg, RUSSIA; Bo Monemar, Linkoping Univ, Dept of Physics and Measurement Technology, Linkoping, SWEDEN.

We report on the effects inversion domains (IDs) on optics of the GaN/AlGaN QWs grown by plasma-assisted molecular beam epitaxy on (0001) sapphire, using high temperature $Al_{0.1}Ga_{0.9}N$ buffer layer. Absorption spectra have been measured additionally to reflection and *cw* photoluminescence (PL). *In-situ* RHEED studies confirm that the structures have generally N-polarity, implying the Ga-polarity for the IDs observed by transmission electron microscopy. The change of the growth regimes (temperature and flux ratio) allowed us to vary the strain and morphology, including the density of the IDs, along the sample surface. The PL signal is extremely low on the part of the samples free from the IDs. At high ID density, PL is rather bright, exhibiting two bands separated by ~100 meV. Attribution of these bands to the basic quantum well layer and IDs, as well as the origin of the gap are discussed in terms of strains, built-in electric fields and growth rate difference in those regions.

L11.17
SIGNIFICANTLY ENHANCED BAND-EDGE PL EMISSION FROM GALLIUN NITRIDE GROWN ON SILICON(111) SUBSRATE.
Muchang Luo, Xiaoliang Wang, Jinmin Li, Hongxin Liu, Lei Wang, Yiping Zeng, Lanying Lin, Novel Semiconductor Material Laboratory, Institute of Semiconductor, Chinese Academy of Sciences, Beijing, P.R. CHINA.

The growth of hexagonal GaN on Si(111) has been performed by gas source molecular beam epitaxy with ammonia. We found that crack-free GaN epilayer thicker than 1.5m could be obtained by mixed use of AlN/GaN superlattice and LT-GaN and AlN intermediate layers. Meanwhile, an interesting phenomenon was observed by photoluminescence (PL) spectra measurements. It shows that the band-edge emission from GaN epilayer is intensified with increasing of AlN/GaN superlattice period. Particularly, by combining use AlN/GaN superlattice and LT-GaN buffer layer, the intensity of band-edge PL spectra is 2.5 times stronger than that of our best GaN sample grown on sapphire substrates. This is indicative of improvement of GaN quality by using AlN/GaN superlattice and LT-GaN buffer.

L11.18
OPTICAL PROPERTIES OF CUBIC GaN DOPED BY Si.
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The optical and reduced bandgap energies and the dielectric functions of Si donor cubic GaN have been investigated experimentally and theoretically. Experimentally by transmission (TR), photoluminescence (PL) and spectroscopic ellipsometry (SE). Theoretically by an ab initio full- potential linear augmented plane wave method as well as within a framework of the many-particle random phase approximation with the Hubbard local-field correction. The cubic GaN:Si epilayers were grown by an rf plasma- assisted MBE on semi-insulating GaAs (001) substrates. We have observed a shift of the bandgap to higher energies with increasing Si-doping for PL and TR spectroscopies. The obtained MNM transition is found at concentraion of Si, about 1E18cm-3. The calculated bandgap energies and dielectric functions were found in good agreement with the measurements.

L11.19
TEMPERATURE-INDUCED CHANGES IN OPTICAL REFLECTIVITY FROM MOCVD-GROWN AlN/GaN HETEROSTRUCTURES.
I.M. Tiginyanu, V.V. Ursaki, N.N. Syrbu and V.V. Zalomai, Laboratory of Low-Dimensional Semiconductor Structures, Technical Univ of Moldova, Chisinau, MOLDOVA; S.M. Hubbard and D. Pavlidis, Dept of Electrical Engineering and Computer Science, Univ of Michigan, Ann Arbor, MI.

Optical reflectivity was used to characterize AlN/GaN heterostructures grown on sapphire substrates by low-pressure MOCVD techniques. Standard precursors of trimethylgallium, trimethylaluminum and ammonia were used as alkyl and hydride sources [1]. The quality of the 1.3 μm thick GaN layers and the presence of AlN thin (3 to 35 nm thick) films were confirmed using high-resolution X-ray diffractometer. The reflectivity spectra measured at 10 K consist of major features at 3.484 and 3.494 eV related to the A and B free exciton ground states as well as of weak features at higher energies related to A and B exciton excited states and to the ground state of the C exciton. Sharp variations in optical reflectivity were observed when cooling and heating AlN/GaN heterostructures between room temperature and 10 K. The reflectivity was found to decrease at a definite temperature T_k in the downward temperature run, and to recover at $T_r > T_k$ in the subsequent upward temperature run. At the same time we observed discontinuities in the temperature dependence of the energy position of A and B excitons. The essence is that the exciton lines exhibit a sharp energy shift of 5 meV at the temperatures involved, the shift being negative in downward and positive in upward temperature runs. According to our analysis, it means that the biaxial strain is reduced by 0.2 GPa at T_k when the sample is cooled, and it is increased by the same value at T_r when the sample is heated. The temperature behavior of reflectivity proves to exhibit memory on the cooling-heating cycles previously subjected to samples. To explain the observed phenomena we propose a model taking into account the sample morphology and the temperature dependence of strain in GaN layers. [1] S.M. Hubbard et al.: Mater. Sci. & Eng. B, 91/92 (2002) 336.

L11.20
COMPOSITION DEPENDENCE OF THE NONLINEAR COEFFICIENTS OF AlGAN FILMS GROWN ON SAPPHIRE SUBSTRATES BY MOCVD AND HVPE.
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The wide transparency range of AlxGa1-xN alloys, coupled with their non-vanishing second-order susceptibilities, make these materials candidates for the realization of ultraviolet nonlinear optical devices. It is therefore important to explore the compositional dependence of the nonlinear coefficients in these materials. Several samples were grown by MOCVD and HVPE and spanned a composition range from x = 0 to roughly x = 0.59. The Al compositions of the samples were determined using energy-dispersive X-ray spectroscopy analysis and the uncertainty in x was approximately ± 0.02. A Nd:YAG laser operating at 1064 nm was used as a pump source to generate rotational Maker fringes at 532 nm from the samples and a crystalline quartz reference plate. The thickness and refractive indices of the AlGaN samples were separately calculated using prism-coupling analysis and these data were used to fit simulations to the measured Maker fringes. The nonlinear coefficients of the samples were measured relative to the quartz reference (chi11 = 0.64 pm/V). For x = 0, the respective values of chi31 and chi33 were 5.5 ± 0.1 pm/V and 11.0 ± 2.0 pm/V, in reasonable agreement with published work. As x increased to roughly 0.3, the postulated constraint chi33 = -2chi31 was maintained. However, this relation failed for higher Al concentration and chi33 was observed to approach zero for x > 0.4. X-ray diffraction analysis revealed sample-to-sample scatter in the lattice constants with increasing x which qualitatively correlated with the observed trend of the chi33 nonlinear coefficient. AFM measurements of the sample surfaces found no correlation between surface roughness/morphology and the trend in the nonlinear coefficients. These results suggest the possibility of fabricating layered structures with modulated nonlinear coefficients for enhancing phase matching for second-harmonic and sum-frequency generation devices.

L11.21
MEASUREMENTS OF THE REFRACTIVE INDICES OF MOCVD AND HVPE GROWN AlGaN FILMS USING PRISM-COUPLING TECHNIQUES CORRELATED WITH SPECTROSCOPIC REFLECTION/TRANSMISSION ANALYSIS.
Norman A. Sanford, National Institute of Standards and Technology, Boulder, CO; Lawrence H. Robins, Albert V. Davydov, Alexander J. Shapiro, National Institute of Standards and Technology, Gaithersburg, MD; Denis V. Tsvetkov, Vladimir A. Dmitriev, Technologies and Devices International Inc., Silver Spring, MD; Stacia Keller, Umesh K. Mishra, Steven P. DenBaars, University of California, Santa Barbara, CA.

Prism-coupling methods were used to measure the ordinary and extraordinary refractive indices of AlxGa1-xN films grown on sapphire substrates by HVPE and MOCVD. The sample sizes were roughly 5 mm x 5 mm. The measured effective indices of ordinary- and

extraordinary-polarized guided modes were used in conjunction with procedures that considered the birefringence of both films and substrates to compute the refractive indices for the AlxGa1-xN films. Several discrete wavelengths ranging from 442 nm to 1064 nm were used and the results were fit to one-term Sellmeier equations. The estimated uncertainty in the refractive index measurements was 0.005 and the estimated uncertainty in the self-consistent calculation for film thickness was 15 nm. Additionally, Curve-fitting analysis of normal-incidence spectroscopic transmittance and reflectance (r/t) measurements, correlated with the prism-coupling results, was used to determine the ordinary refractive index as a continuous function of wavelength from 200 nm to 2500 nm. It was necessary to fit these r/t results with two-term Sellmeier equations in order to accommodate this wider wavelength range. The Al compositions of the samples were determined using energy-dispersive X-ray spectroscopy analysis (EDS). EDS measurements were taken near the center and corners of a sample under test and the results averaged. HVPE grown samples had compositions x = 0.279, 0.363, 0.593, and 0.657. MOCVD samples had x = 0.00, 0.419, 0.507, 0.618, 0.657, 0.660, and 0.666. The typical variation in x across a sample was +/- 0.003. This level of precision was further justified since the refractive index difference at 442 nm of samples with x = 0.660 and x = 0.666 was just resolved. However, the estimated accuracy in the EDS determined value for x was 0.02. Limited experiments on the effects of Si doping (at roughly 5e18 cm-3) revealed negligible effects on refractive index.

L11.22
OPTICAL BAND GAP MEASUREMENTS OF InN FILMS IN THE STRONG DEGENERACY LIMIT. D.B. Haddad, Dept. of Physics, Wayne State University, Detroit, MI; Y.V. Danylyuk, Dept. of Electrical and Computer Engineering, Wayne State University, Detroit, MI; J.S. Thakur, School of Physics, University of New South Wales, Sydney, AUSTRALIA; V.M. Naik, Department of Natural Sciences, University of Michigan-Dearborn, Dearborn, MI; R. Naik, Dept. of Physics, Wayne State University, Detroit, MI; G.W. Auner, Dept. of Electrical and Computer Engineering, Wayne State University, Detroit, MI; L.E. Wenger, Dept. of Physics, Wayne State University, Detroit, MI.

InN thin films (~0.5 μm) have been grown on sapphire substrates by plasma source molecular beam epitaxy deposition. X-ray diffraction measurements show that the films are wurtzite polycrystalline at a growth temperature of 325 °C, whereas a completely c-axis textured growth at a temperature of 475 °C. The optical transmission data on these samples show not only a band gap absorption, but also a plasmon absorption due to a high level of carrier concentration (strong degeneracy limit). This is further supported by the presence of a plasmon-LO-phonon (PLP) mode in Raman spectra of InN. The Raman bands, A_1 (LO) and E_2, are rather broad indicating the presence of a large number of structural defects. Furthermore, the well defined plasmon edge in the reflectance data of these samples was fitted, with a semi-infinite medium approximation using known values for dielectric constant and effective mass of an electron in InN, to determine the electron carrier concentration in InN. These values are in the range of 2×10^{20} - 4×10^{20} cm^{-3}, which were further confirmed from Hall effect measurements data. The band gap absorption data were analyzed assuming a direct band gap and also incorporating the Moss-Burstein shift effect. The calculated values for intrinsic band gap energy are smaller (~ 1 eV) than the observed values (1.6-2.0 eV).

L11.23
A STUDY OF INDIUM NITRIDE FILMS GROWN UNDER CONDITIONS RESULTING IN APPARENT BAND-GAPS FROM 0.7 TO 2.3 ELECTRON VOLTS. K. Scott A. Butcher, Marie Wintrebert-Fouquet, Trevor L. Tansley, Physics Department, Macquarie University, Sydney, AUSTRALIA; Motlan, Department of Physics, Faculty of Mathematics and Science, State University of Medan, INDONESIA; Heiko Timmers, Santosh Shrestha, School of Physics, University of New South Wales, Australian Defence Force Academy, Canberra, AUSTRALIA.

In recent publications a number of groups have proposed that the band-gap of indium nitride, long established at 1.89 eV, might be as low as 0.7 eV. We present analysis data, including SIMS, elastic recoil detection analysis (using heavy ions) and UV-Vis transmission measurements, for samples that span this apparent range of band-gap. This data is presented in an effort to determine the reasons for the wide spread of reported band-gap values.

L11.24
COMPOSITION DEPENDENCE OF THE FUNDAMENTAL BAND GAPS OF GROUP III-NITRIDE ALLOYS. J. Wu, W. Walukiewicz, K.M. Yu, J.W. Ager III and E.E. Haller, Division of Materials Sciences and Engineering, Lawrence Berkeley National Laboratory, and University of California, Berkeley, CA; Hai Lu and William J. Schaff, Department of Electrical and Computer Engineering, Cornell University, Ithaca, NY.

It has been reported recently [1] that the energy gap of wurtzite-structured InN is only about 0.77 eV, much smaller than the previously published value of 1.9 eV. This discovery greatly expands the spectral range covered by the direct band gaps of group III-Nitride ternary alloys. They now cover photon energies from the near infrared (InN) to the deep ultraviolet (AlN). To fully realize this new potential of the group III-nitrides, there is a need to determine the optical properties of the low gap nitride alloys. Here we report our studies of the optical properties of In-rich $In_{1-x}Ga_xN$ and $In_{1-x}Al_xN$ alloys with $1<x<0.5$ and $1<y<0.24$, respectively. High-quality thin films of these alloys were grown by molecular beam epitaxy on sapphire substrates. The fundamental band gaps were measured using optical absorption, photomodulated reflection (PR) and photoluminescence (PL). For all alloy compositions, we observed a well-resolved absorption edge and a strong room-temperature PL signal. The band gaps of these alloys increase monotonically with decreasing In content. The composition dependence of the band gaps is well described by a second order polynomial with a bowing parameter of 1.4 eV for $In_{1-x}Ga_xN$ and 3.0 eV for $In_{1-x}Al_xN$ alloys. These bowing parameter values are much smaller than the ones previously determined by fitting the composition dependence of the energy gaps of samples with small In content using a gap energy of 1.9 eV for InN. The PL peak position is red-shifted from the absorption edge. The shift increases with increasing Ga or Al content and is as large as 0.5 eV in $In_{0.5}Ga_{0.5}N$. We also observed a significant change in the temperature and pressure coefficients of the band gaps in In-rich $In_{1-x}Ga_xN$ and $In_{1-x}Al_xN$ alloys. [1] V. Davydov, et. al., phys. status solidi B 229, R1 (2002). [2] J. Wu et. al., Appl. Phys. Lett. 80, 3967 (2002).

L11.25
PRESSURE DEPENDENCE OF ENERGY BAND GAPS FOR InAlN. Z. Dridi[a,b], B. Bouhafs[a,b], and P. Ruterana[a]; [a]ESCTM-CRISMAT, UMR6508-CNRS, ISMRA 6, Caen, FRANCE; [b]LSMSM, Departement de Physique, Faculte des Sciences, Universite de Sidi-Bel-Abbes, Sidi-Bel-Abbes, ALGERIE.

Using first-principles method, we study the effect of pressure on the bands gap energy of wurtzite InAlN. Starting by the binaries, InN, and AlN, the direct band gap is found to increases linearly with pressure but becomes indirect for AlN at 13.88 GPa. The direct band gap pressure coefficients are 18.8 meV/GPa for InN, and 40.5 meV/GPa for AlN, which are in good agreement with other calculations. For the ternary alloy, the fundamental band gaps energy are direct and increase rapidly with pressure. The pressure coefficients vary in the range of 16.7-20.7 meV/GPa; they depend on alloy composition with a strong deviation from linearity. The band gap bowing of InAlN strongly decrease when the AlN band gap becomes indirect.

L11.26
ELECTRICAL AND OPTICAL PROPERTIES OF InN/Si HETEROSTRUCTURE. Kazuhiro Mizuo, Tomohiro Yamaguchi, Yoshiki Saito, Tsutomu Araki, Yasushi Nanishi, Ritsumeikan Univ, Dept of Photonics, Shiga, JAPAN.

InN has been understood to have a direct bandgap of 1.9eV. However, it is reported very recently that the bandgap energy of InN is less than 1eV[1][2]. Not only the bandgap energy but other physical properties are also not known enough to be applied to photonic and electronic devices. Therefore, in order to clarify the real potential of InN-based devices, we attempted to fabricate p-n junction between InN and Si substrate. InN/Si system also has advantages in application for the monolithic integration of photonic and electronic devices and high efficiency tandem solar cells. However, it is difficult to grow InN on Si substrates due to large lattice mismatch and low dissociation temperature. In this paper, we will report on electrical and optical properties of InN/Si. We succeeded in the growth of single crystalline InN films on Si substrates. Rectifying characteristic in n-InN/p-Si heterostructure was also obtained for the first time.
InN films were grown at 390°C for 1 hour by RF-MBE. The substrate used in this study was p-type Si(111) with resistivity of 0.02Ω·cm. Film thicknesses of the InN were 250nm. Undoped InN films showed n-type conductivity with carrier concentration of more than $1\times10^{19}cm^{-3}$.
Rectifying characteristics were confirmed by the current-voltage (I-V) measurement at room temperature. This result indicates that the interface between InN and Si forms p-n junction. Effects of low temperature buffer layer deposition and nitridation process of the Si substrate on the junction property of InN/Si were also investigated. It is found that both the buffer layer deposition and the nitridation process caused big changes in forward I-V characteristic.
Optical properties of InN/Si were also investigated by photoluminescence technique. Strong PL peak was observed at around 0.8eV, which was much smaller than reported PL emission peak of ~2eV[3].

[1]V.Y. Davydov et al. phys. stat. sol. (b) 3(2002)R1.
[2]J. Wu et al. Appl. Phys. Lett. 80(2001)3967.
[3]T. Yodo et al. Appl. Phys. Lett. 80(2002)968.

L11.27
OPTICAL PROPERTIES OF CONTROLLABLE SELF-ASSEMBLED LATERAL NANOSTRUCTURES ON InN, InAlN, AND AlN THIN FILMS. Yuriy Danylyuk, Dmitri Romanov, Eric McCullen, Gregory Auner, Wayne State University, Dept of Electrical and Computer Engineering, Detroit, MI; Daad Haddad, Ratna Naik, Wayne State University, Dept of Physics, Detroit, MI.

Utilizing plasma source molecular beam epitaxy (PSMBE), we have grown InN, InAlN, and AlN films on (0001) sapphire substrates. The value of indium concentration in InAlN films varied from 0 to 1. In all the obtained films, high resolution X-ray diffraction scans (XRD) show monocrystal quality and no face segregation. The atomic force microscopy reveals characteristic surface patterns of nanometer scale. The characteristic feature size and the size distribution are determined by the film composition and thickness, as well as by the thickness of the buffer layer in the case of In-containing films. X-ray photoelectron spectroscopy (XPS) analysis indicates presence of a small number of N vacancies and O imputrities. We have thoroughly studied optical properties of the films by UV/VIS optical absorption and reflection spectroscopy. Both absorption and reflection spectra demonstrate additional peaks below the fundamental absorption threshold. These peaks cannot be associated with the mentioned N vacancies or any other known crystal defects and impurities. We attribute these additional peaks to the quantum states of electrons confined in the hillocks of the lateral structure by the strong electric field of piezoelectric and built-in polarization that is characteristic to nitride semiconductor compounds. The calculated values of the electron energy levels are in good agreement with the spectroscopic data; moreover, the hillock confinement model explains the observed temperature dependence of the additional peaks. Control of the characteristic feature size of lateral nanostructures by means of growth technology modifications opens an easy way to control the optical and transport properties of the films.

L11.28
A STUDY OF DECOMPOSITION OF GaN DURING ANNEALING. M.A. Rana, M.B.H. Breese, T. Osipowicz, F. Watt, Research Centre for Nuclear Microscopy, Department of Physics, National University of Singapore, SINGAPORE; H.W. Choi, S.J. Chua, Department of Electrical Engineering, Centre for Optoelectronics, National University of Singapore, SINGAPORE.

Annealing experiments were carried out on GaN layers which were grown on sapphire through Metal Organic Chemical Vapour Deposition (MOCVD). Samples were annealed between temperatures of 500 $^{\circ}C$ to 1100 $^{\circ}C$ for time intervals ranging from 15 seconds to 180 seconds. Random and channelling Rutherford backscattering experiments were performed on as-grown and annealed GaN samples using 2 MeV proton and He ion beams to study the processes caused by annealing in GaN and to examine its effects on GaN crystalline quality and stoichiometry. No decomposition was measured for temperatures up to 800 $^{\circ}C$. Decomposition in the near-surface region increased rapidly with the further increase in temperature, resulting in a near-amorphous surface-region for annealing at 1100 $^{\circ}C$. Incorporation of oxygen in GaN was also measured in the disrupted region due to vacancies produced after evaporation of nitrogen and gallium during annealing. We describe the range of annealing conditions under which negligible decomposition of GaN is observed, which is important in assessing optimal thermal processing conditions of GaN.

L11.29
STUDIES OF ELECTRON INJECTION-INDUCED EFFECTS IN III-NITRIDES. Leonid Chernyak, University of Central Florida, Dept of Physics, Orlando, FL.

The transport properties of minority carriers are an important indicator for the quality of GaN and related materials. One of the main difficulties that must be overcome in GaN, is a reduced minority carrier diffusion length. On the other hand, minority carrier diffusion determines a performance of bipolar electronic devices, including photovoltaic detectors quantum efficiency. Enhancement of minority carrier diffusion presents a serious technological challenge, since this can not simply be achieved by the growth of low defect level material. Limitations, especially in heteroepitaxy, arise from the lattice mismatch between GaN epitaxial layer and the underlying substrate. To obtain a pronounced increase of minority carrier diffusion length merely by reduction of carrier scattering on the dislocation walls, the threading dislocation density must be significantly reduced. We recently found that electron injection into p-(Al)GaN - either from the electron beam of a Scanning Electron Microscope (SEM) or from the application of an external voltage in a solid state device - increases the critical minority carrier diffusion length and lifetime. Consistent changes were observed in the material's optoelectronic properties, including photoresponse, and were attributed to charging of Mg-dopant-related centers. The novel effects, induced by electron injection in III-Nitrides, and the ways to exploit them for tailoring the materials fundamental properties will be discussed. Application of the effects for performance improvement of photovoltaic UV detectors will be demonstrated.

L11.30
ELECTRON STIMULATED DESORPTION OF DEUTERIUM FROM GaN(0001). Y. Yang, J. Lee, and B.D. Thoms, Georgia State University, Atlanta, GA.

The desorption of hydrogen atoms from GaN surfaces is an important step in GaN growth (by MOCVD and HVPE), doping (particularly Mg) and etching (e.g. RIE) processes. Mapping the removal of hydrogen requires understanding both the transport of hydrogen to the surface and desorption from the surface. The authors earlier work on temperature programmed desorption (TPD) from deuterated GaN(0001) surfaces with a heating rate of 1 K/s shows that D_2 recombinatively desorbs in two peaks, the main peak at 690 K and a smaller peak near 600 K, indicating at least two surface or subsurface adsorption sites. In this paper we perform electron stimulated desorption (ESD) on deuterated GaN(0001) to further characterize these adsorption sites. A wide spot electron gun supplies up to 500 μA of electrons for ESD. TPD after a saturation exposure to 90 eV electrons shows that the D_2 peak at 690 K is removed while the peak at 600 K remains almost the same intensity. It also reveals a smaller feature at 730 K that is hidden by the 690 K peak in TPD curves acquired without electron exposure. Deuterium desorption at 600 K and 730 K is proposed to be from subsurface sites, since these features are not removed by substantial electron exposure. These desorption features will be correlated with changes in the electron structure observed using electron energy loss spectroscopy (ELS).

L11.31
ELECTRONICALLY ENHANCED DIFFUSION IN GaN. Yutaka Mera, Koji Maeda, Dept. of Applied Physics, The University of Tokyo, Tokyo, JAPAN; Kunio Suzuki, Institute of Industrial Science, The University of Tokyo, Tokyo, JAPAN.

It is known that decomposition or evaporation of GaN crystals occurs when they are irradiated with a high-density of electrons in transmission electron microscopes (TEM). We have found that the perforations or the dimples formed in the TEM films by irradiation of a focused electron beam recover to flat films when we irradiate the films with a moderately defocused electron beam. Experimental results strongly suggest the occurrence of surface self-diffusion enhanced by the electron-beam irradiation. Three possible mechanisms are conceivable for the enhancement of self-diffusion: 1) knock-on damage 2) beam heating 3) an electronic excitation effect. A recovery at 120keV, which is below the damage threshold of GaN crystal, rules out a simple effect of knock-on damage by the electron beam. The temperature rise caused by the relatively small total electron current from the field emission gun is estimated to be less than 0. 1K using 1.3 W/cmK as thermal conductivity of GaN. Furthermore, one of results indicates that the sample temperature have not risen above 156.6C, a melting point of indium. Thus, it is quite likely that the recovery is induced by self-diffusion enhanced by electronic excitations due to electron beam irradiation.

L11.32
BAND-LIKE AND LOCALIZED STATES INDUCED BY IRRADIATION IN HVPE N-GaN. Antonio Castaldini, Anna Cavallini, Laura Polenta, INFM and Dipartimento di Fisica, Bologna, ITALY.

This paper deals with defects induced by proton irradiation in n-GaN. The samples were HVPE grown, irradiatied with 24 GeV protons. DLTS was performed on both as-grown and irradiated samples with two different diode structures. Planar structures were used, where Au metallization was performed on the epilayer surface. Additionally, Au diodes were metallized on the epilayer-substrate lateral surface to probe the most dislocated region close to the substrate/epilayer interface. Two electron traps were identified in the as-grown material with both diode structures: trap EC1 (EC 0.19eV) and trap EC2 (EC 0.25eV), EC2 being the dominant one. However, while in planar structure the two peaks are partially overlapped, in cross-sectional investigations EC1 and EC2 are well resolved. The irradiation consistently affects the preexisting levels in a way depending on the diode structure, hence on the region probed by DLTS. With planar diode structures the trap EC1 density more significantly increases with irradiation, becoming the dominant one, while with cleaved cross-sectional diode structures the trap EC2 dominates also after irradiation. This contribution focuses on the different nature of the deep levels associated to EC1 and EC2. Their filling kinetics has been

studied since, for what said above, we suspected that EC2 would be associated to extended defects, as already reported in literature. Indeed, the site density of EC2 logarithmically depends on the filling pulse width, demonstrating that this trap is associated to an extended defect, the potential barrier Δ of which was determined. The trap EC1, on the contrary, exhibits the filling kinetics peculiar of point defects but the features of its DLTS spectra indicate that these defects are band-like.

L11.33
HIGH-TEMPERATURE ILLUMINATION-INDUCED METASTABILITY IN UNDOPED SEMI-INSULATING GaN GROWN BY METALORGANIC VAPOR PHASE EPITAXY.
Z-Q. Fang, B.B. Claflin, D.C. Look, Wright State Univ, Semiconductor Research Center, Dayton, OH; T.H. Myers, West Virginia Univ, Physics Dept, Morganton, WV; D.D. Koleske, A.E. Wickenden, R.L. Henry, Naval Research Laboratory, Electronics Science and Technology Division, Washington, DC.

Undoped semi-insulating (SI) GaN films are preferred for device structures such as AlGaN/GaN HEMTs. Recently, yellow-luminescence related optical metastability or memory effects in undoped epitaxial GaN have been studied by using photoluminescence (PL) or cathodoluminescence (CL), in conjunction with exposures of samples to either high-intensity ultraviolet light or an electron beam at room temperature [1,2]. Instead of PL or CL, we have successfully used thermally stimulated current (TSC) spectroscopy and temperature-dependent photocurrent (PC) to study metastability in undoped SI-GaN samples grown by metalorganic vapor phase epitaxy. The metastability is induced by high-temperature illumination at 390>T>300 K (using white light with or without a 360-nm band pass filter), followed by cooling the sample to 83 K in the dark. Without the high-temperature illumination, the SI-GaN sample stays in its normal state (or "off" state) and shows at least six TSC traps, B (0.63 eV), Bx (0.51 eV), C1 (0.44 eV), C (0.32 eV), D (0.23 eV), and E (0.16 eV), which are very similar to electron traps found in n-type GaN films by using deep level transient spectroscopy. With the high-temperature illumination, the sample goes into a metastable state (or "on" state), and shows a strong increase in both the PC at 83 K and the TSC of traps D, C, and E, accompanied by a significant change in the relative densities of these traps. Persistent PC at 83 K in "on" state lasts much longer than that in "off" state. Based on the temperature and illumination-time dependences of the PC, and the relative sizes of the TSC traps in the "on" and "off" states, we discuss how point defects and dislocations may influence the metastability. [1] Y.C. Chang et al., Appl. Phys. Lett. 79, 281 (2001). [2] Y.C. Chang et al., Appl. Phys. Lett. 80, 2675 (2002).

L11.34
SUPPRESSING OF OPTICAL QUENCHING OF DEEP DEFECT-TO-BAND-TRANSITIONS IN GaN/AlGaN HETEROSTRUCTURES WITH HIGH Al CONTENTS.
H. Witte, E. Schrenk, K. Flügge, A. Krtschil, A. Krost, J. Christen, Otto-von-Guericke-Universität Magdeburg, Institute of Experimental Physics, GERMANY.

Deep defect-to-band-transitions were investigated by photocurrent spectroscopy (PC), optical admittance spectroscopy (OAS) and photo-Hall-effect measurements in n-type AlGaN structures with an GaN top layer (60nm thick). The Al content in the AlGaN layers varied between 0 and 24%. The samples were grown on sapphire substrates using metal organic chemical vapor deposition and Schottky contacts were fabricated on the GaN top layers. The optical transitions of the GaN and the AlGaN layer were well separated using OAS and PC by variation of the bias voltages, i.e. in forward bias direction the GaN layer and in reverse direction the AlGaN layer is dominant. Light of below band gap photon energy was used for optical quenching. In forward direction (GaN layer) the quenching effect is much stronger than in the reverse direction (AlGaN layer). The quenching effect strongly depends on the Al-content of the AlGaN layer, rapidly decreasing with increasing [Al] and becoming completely suppressed at about [Al] = 20%. Similar effects were observed in multiple GaN/AlGaN layer systems. The origin of the optical quenching will be discussed in terms of deep defects. In AlGaN layers with [Al] < 8% the dominant bands in PC and OAS corresponding to deep defects with optical transition energies between E_G-(0.08 eV and 0.2 eV) and E_G-(0.2 eV and 0.7 eV) were effectively quenched. The related traps were identified using thermally stimulated current and thermal admittance spectroscopy. Our results support the model of multiple recharching processes of deep defects e.g. for metastable or multiple charged states described by Huang et all. (J. Appl. Phys. 82 (1997), 2707) for GaN and by Alvarez et al. (Appl. Phys. Lett. 68 (1996), 2959) for GaAs.

L11.35
SPECTROSCOPIC CHARACTERIZATION OF ION-IMPLANTED GaN.
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Ion implantation is of interest as a selective doping technique for GaN. Encapsulation and annealing procedures are not as well developed for this material as for more conventional semiconductors because of the high annealing temperatures required. The behavior of ion implanted impurities and interactions with defects is not as yet well understood. Here, we describe an investigation of high purity GaN layers implanted with a variety of impurities, including Mg, Be, C, Zn, Cd, Ca, N, O, P, As, Ne, and Ar, including some co-implantation studies. After implantation, the samples are annealed at 1300°C using sputtered AlON encapsulation. The resulting material is characterized using low temperature photoluminescence (PL). We show that Mg acceptors exhibit much better optical activation under the same conditions than Be, C, Zn, Cd, or Ca acceptors. The heavier ions are believed to require annealing at even higher temperatures, which is in progress. We show that both Be and C implantation strongly enhance a yellow (2.2 eV) PL band, but that none of the impurities do so, including O. Highly resolved spectra of excitons bound to isoelectronic As or P impurities are obtained with sharp no-phonon lines at 2.952 and 3.200 eV, respectively, and a complicated phonon sideband. The P impurities are shown to switch to the Ga site and produce new double donor-acceptor pair recombination bands when co-implanted with Mg, due to a Fermi level effect on their incorporation. Sharp acceptor-bound exciton peaks and well-resolved donor-acceptor pair bands are observed for both Mg and Zn. A broad peak centered near 2.78 eV is obtained for Cd implantation, confirming that it is deeper than Zn.

L11.36
CATHODOLUMINESCENCE CHARACTERIZATION OF ION IMPLANTED AlN.
J. Zenneck, U. Vetter, H. Hofsäss, and C. Ronning, II. Physikalisches Institut, Universität Göttingen, Göttingen, GERMANY.

The processing of conventional semiconductors like Si or GaAs using ion implantation is a routinely task. This is also highly desired for the group III-nitrides that experienced a triumphal procession in optoelectronics in recent years. However, the basic processes and recovery mechanism during ion implantation and subsequent thermal processing of GaN and related materials are still an open issue [1] and many research programs failed in an adequate activation of implanted impurities. Detailed and systematic investigations of the luminescence of implanted III-nitrides and its annealing behavior allows drawing conclusions on the recovery of implantation defects, on the doping efficiency and on the micro structural environment of the implanted dopant. For this proposes, single crystalline (0001) aluminum nitride (AlN) layers were implanted with the acceptor magnesium as well as with rare earth elements that possess sharp intra-shell transitions from the infrared to ultra-violet regime. Subsequently annealing within the range of 600-1100 C for 10 minutes was performed in vacuum or nitrogen atmosphere. The obtained CL-results will be presented together with a comparative analysis to ion implanted GaN [1]. [1] C. Ronning, E.P. Carlson, R.F. Davis, Phys. Rep. 351 (2001) 349-385

L11.37
PHOTOCONDUCTIVITY OF GaN FILMS PRODUCED BY MBE AND MOCVD.
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Photoconductivity is a powerful tool to probe defect states in the gap of a semiconductor. Specifically, by varying the positions of the quasi-Fermi levels of electrons and holes through the variation of the illumination level, one can probe the distribution and the interaction of the trap and recombination centers in the semiconductor. In this paper we report on photoconductivity studies in GaN films grown either by plasma-assisted MBE or MOCVD. Measurements were done using interdigitated metal stacks, patterned photolithographically and subjected to rapid thermal annealing to form Ohmic contacts. Both conducting films with resistivity less than102 (Ohm. cm) and semi-insulating films with resistivity more than 106 (Ohm. cm) were investigated. The magnitude of the photoconductivity as well as the photoconductivity response time was studied as a function of light intensity and temperature. From room temperature measurements we find that while the photoconductivity of the semi-insulating films depends linearly on light intensity over a wide dynamic range, the photoconductivity of the conducting films varies linearly at low light intensities and as I0.5 at high light intensities. These results are consistent with a model, which assumes an exponential distribution of traps from the band edges. The bimolecular dependence is consistent is with a sharp exponential trap distribution clustered close to the band edges, while the monomolecular dependence is consistent with a broad exponential trap distribution extending deep into the gap. We theorize that the origin of this exponential distribution of traps is static disorder associated with strain from point defects (vacancies,

interstitials, antisite defects and impurities). The recombination kinetics as a function of temperature is derived by studying also the temperature dependence of the photoconductivity response time as well as the () product, determined from photoconductivity gain measurements.

L11.38
PLANE-WAVE PSEUDOPOTENTIAL STUDY ON MECHANICAL AND ELECTRONIC PROPERTIES FOR GROUP III-V SEMICONDUCTORS. S.Q. Wang, H.Q. Ye, Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, Shenyang, P.R. CHINA.

The results of first-principle density functional calculation of the bulk moduli and related structural and electronic properties of group III-V nitride, arsenide, phosphide and antimonide with zincblende and wurtzite structures are presented. The energy band structure variations of these semiconductors under high pressures are studied, systematically. The result of pressure relations of the energy band structures shows sublinear relationship for most of these phases except a few In-V and Ga-V zincblende phases, which have to be described by two linear functions. It is found that the wurtzite phases are generally more sensitive to pressure than their zincblende counterparts. The cell volume dependence of bulk modulus for these phases is investigated. Linear relationship between the bulk moduli and the unit-cell volumes, respectively for zincblende and wurtzite phases, are found. It is suggested that this linear relation arises from the same crystallographic configuration of the phases.

L11.39
USE OF MECHANICAL BENDING FOR DETERMINATION OF DEFORMATION POTENTIALS FOR THE E_2(high) PHONON MODE OF AlN. A. Sarua and M. Kuball, Physics Department, University of Bristol, Bristol, UNITED KINGDOM; J.E. Van Nostrand, Air Force Research Laboratory, Wright-Patterson Air Force Base, OH.

AlN and its alloys are one of the most attractive semiconductor materials for UV optoelectronics and high-power and high-frequency electronic applications. However, there is still little known about its elastic properties, in particular about phonon deformation potentials (DPs), which link phonon frequencies with the amount of stress/strain in the material. Since Raman spectroscopy can be applied to detect non-invasively strain and stress fields in epitaxial semiconductor layers and device structures, knowledge of deformation potentials is crucial. In this contribution, we report on the determination of the E_2(high) phonon DPs for hexagonal AlN. In contrast to previous works, where strain in AlN was estimated from X-ray diffraction(XRD) measurements, we avoid inaccuracy inherent to this method, such as the need to use reference values of unstrained AlN and comparison between AlN grown on different substrates. The DPs for the E_2(high) phonon mode were obtained from Raman measurements on am AlN/Si(111) sample, where biaxial stress was applied by mechanical bending. The amount of strain introduced was obtained by measuring the phonon frequency of the Si substrate, this avoids the use of XRD. A value of the DP $\tilde{\alpha} = 1.5 \pm 0.1$ cm^{-1}/GPa was determined taking into account different values of elastic constants reported for AlN in the literature. This gives an E_2(high) frequency shift of about 3 cm^{-1}/GPa for the biaxial stress in AlN. Theoretical calculations [1] underestimate this value by 20-30%. [1] J.-M. Wagner and Bechstedt, Appl. Phys. Lett. 77, 346 (2000).

L11.40
SURFACE PASSIVATION OF AlGaN TERMINATED AND GaN TERMINATED HEMT STRUCTURES. B.P. Gila, E. Lambers, A.H. Onstine, K.K. Allums, C.R. Abernathy, S.J. Pearton, University of Florida, Dept of Materials Science and Engineering, Gainesville, FL; B. Luo, F. Ren, University of Florida, Dept of Chemical Engineering, Gainesville, FL.

Remarkable progress has been made in the field of high performance and high power AlGaN/GaN high-electron-mobility transistors (HEMTs); namely, in understanding the device physics and demonstrating excellent microwave power performance. One problem with the implementation of these devices is that the rf power obtained is much lower than that expected from the dc characteristics. This rf power decrease is manifested by a drain current collapse that is believed to be caused by the presence of surface states between the gate and drain, which deplete the channel. Several studies have shown that these traps can be passivated with SiN_X, MgO, and Sc_2O_3. Recently, it has been shown that the GaN terminated HEMT structure is more readily passivated than the AlGaN terminated HEMT structure. In this paper we report on the influence of the native oxide on the HEMT structures on the ability to passivate the surface traps. Samples of both AlGaN and GaN terminated HEMT structures were studied using x-ray photo spectroscopy (XPS). It was found that the XPS spectra of both AlGaN and GaN as grown surfaces were shifted by a surface charge of 0.5 to 1.0 eV. The samples were then oxidized using a UV-ozone treatment for 25 minutes at room temperature. The native oxide XPS spectra of the AlGaN terminated surface was found to have the same 0.5 to 1.0 eV shift while the native oxide XPS spectra of the GaN terminated surface was found to have a 5.0 eV shift, indicating that the native GaN oxide is more insulating. Processed HEMT devices using both surface terminations were given the same UV-ozone treatment followed by a 10nm MBE grown MgO film for passivation. The GaN terminated HEMT structures showed on average a 10% increase in channel current (from gate-lag measurements, pulse mode) over the AlGaN terminated HEMT structures.

L11.41
FABRICATION OF AlGaN/GaN HETEROSTRUCTURE FIELD EFFECT TRANSISTOR USING PRE-OXIDATION PROCESS. C.M. Jeon, H.W. Jang, Jae-Hoon Lee[a], Jung-Hee Lee[a], J-L. Lee, Department of Materials Science and Engineering, Pohang University of Science and Engineering, Pohang, KOREA; [a]Department of Electronic and Electrical Engineering, Kyunpook National University, Teagu, KOREA.

The Schottky barrier height (SBH) of gate electrode is an important parameter of HFET. A large barrier height improves transconductance, maximum drain current and breakdown voltage of electronic devices, leads to the increase of power performances. The metal work function of Ni, Pt and Au is greater than other metals. Thus recently, Pt, Ni and Au contacts have been studied for gate electrode of AlGaN/GaN HFET. However, the SBH of Pt, Ni, Au contacts was 0.7 1.0 eV, which is insufficient for power HFET. In AlGaN, V_N act as donors and V_{Ga} are acceptors. If V_{Ga} were generated below the Schottky contact by oxidation process which generated GaO_X by annealing in O_2 ambient at 500 °C and removed the GaO_X using aqua-regia boiling, the Fermi level position would be shifted to the energy level of V_{Ga} and effective SBH increased. However, no works has been studied on the fabrication of AlGaN/GaN HFET using such process. The SBH of Ir Schottky contact on AlGaN/GaN HFET was increased about 0.2 eV and leakage current dramatically decreased after oxidation process at which the specific contact resisvity of Ti/Al/Ni/Au Ohmic contact was $10^{-5}\Omega$cm^2. In order to investigate the mechanism of SBH increase and leakage current decrease in oxidation process, synchrotron radiation photo electron spectroscopy (SRPES) was employed. The SRPES analysis showed that V_{Ga} were generated on the surface after oxidation process. The valence band spectra shifted toward lower binding energy and the secondary cutoff shifted to high kinetic energy. It means that the Fermi level position at surface of AlGaN shifted toward valence band edge through oxidation process. Thus, the SBH of Ir/AlGaN/GaN contact was increased after oxidation process. From these analyses, the effect of oxidation process in Schottky contact on AlGaN will be revealed and the HFET was fabricated.

L11.42
NOVEL GaN-BASED TRANSISTOR GEOMETRY FABRICATED BY PHOTOELECTROCHEMICAL WET UNDERCUT ETCHING. Yan Gao[a], Andreas R. Stonas[b], Ilan Ben-Yaacov[b], Umesh Mishra[b], Steve P. DenBaars[a,b], Evelyn L. Hu[a,b]; [a]Materials Dept., University of California, Santa Barbara, CA; [b]Electrical and Computer Engineering Dept., University of California, Santa Barbara, CA.

In this study, a novel GaN-based transistor geometry, called a CAVET (Current Apertured Vertical Field Effect Transistor) was demonstrated. The critical part of this device is an aperture formed by smoothly undercut etching a 600Å thick $In_{0.07}Ga_{0.93}N$ layer from between two GaN layers. This process was performed by selective photoelectrochemical (PEC) undercut etching. PEC wet etching has previously been shown to be a promising technique for fabricating low-damage GaN-based devices. The doping- and bandgap-dependent nature of PEC wet etching can be used to form three-dimensional device structures by selective etching of a particular layer in a heterostructure [1]. However, in spite of this progress, residual roughness and difficulty in controlling lateral etching remain as concerns for this technique. We have here carried out a systematic optimization to obtain smooth, well-controlled undercuts with front-side illuminated PEC etching. These optimized etching conditions were employed to fabricate CAVETs. The structure and electrical properties of these CAVETs are investigated. The I-V curve will be compared with simulations of this device. Merits of this novel device such as high breakdown voltage and low dispersion will also be discussed. [1] A.R. Stonas, T. Margalith, et al. Development of selective lateral photoelectrochemical etching of InGaN/GaN for lift-off applications. Appl. Phys. Let. 78 (13) 1945-1947, 2001.

L11.43
INVESTIGATION OF SPACER AND N-TYPE LAYER OF DOPED HEMT STRUCTURES USING STATISTICAL MULTI-PARAMETER SOFTWARE EVALUATIONS. A. Alam, B.

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High electron mobility transistors (HEMT) based on *AlGaN/GaN* structures offer great possibilities for high-power and high-frequency microwave applications. The effects of *Al* concentration, n-type layer and spacer thicknesses and the surface morphology on the electrical data were studied in this work. All samples presented here have been grown in an AIX 200 RF MOCVD system on 2" c-plane sapphire wafers, using *TMGa, TMAl, NH_3* and *SiH_4* as precursors. Hall measurements at room and liquid nitrogen temperature were used to determine the electrical data, while the sample roughness was assessed by atomic force microscopy (AFM) and in-situ reflectometry measurements (Filmetrics). The *Al* concentration and n-type layer and spacer thicknesses were determined by Rutherford back scattering (RBS). Powerful statistical multi-parameter software was used to determine the interaction between the parameters and to evaluate the data. This enables us to determine optimum parameter fields for the epitaxial growth with high efficiency and accuracy. While sheet carrier concentration increases linearly with increasing *Al* concentration the mobility decreases simultaneously. The interaction plot shows that this effect is very strong for n-type layer and spacer thicknesses up to 15 and 5 nm, respectively. For n-type layers and spacers below these thicknesses the influence can be neglected. Mobility as well as carrier concentration decrease linearly with the thickness of the n-type layer and the spacer up to 15 nm and to 5 nm, respectively. Surprisingly no correlation between surface roughness and electrical data was found. We determined 6 and 10 nm thicknesses for spacer and n-type layers, respectively, with an *Al* concentration of 18% as optimum. With these parameters for still not optimized HEMT structures (with respect to other parameters) layers were deposited reproducibly with excellent electrical data % ($\mu_{(RT)} = 1560$ cm^2/Vs, % $n_{(RT)} = 1.4 \times 10^{13}$ cm^{-2}, % $\mu_{(77K)} = 7300$ cm^2/Vs, % $n_{(77K)} = 1.4 \times 10^{13}$ cm^{-2}, % $\mu_{(5K)} = 8000$ cm^2/Vs) ($\mu_{(RT)} = 1550$ cm^2/Vs, $n_{(RT)} = 1.03 \times 10^{13}$ cm^{-2}, $\mu_{(77K)} = 4200$ cm^2/Vs, $n_{(77K)} = 1.0 \times 10^{13}$ cm^{-2}, and very smooth surfaces (rms $\ll$ 1 nm). The independence of mobility on temperature below 50 K indicates the presence of a 2-DEG.

L11.44
PROPERTIES OF DELTA DOPED $Al_{0.25}Ga_{0.75}N$ AND GaN EPITAXIAL LAYERS. J.S. Flynn, L.G. Wallace, J.A. Dion, E.L. Hutchins, H. Antunes and G.R. Brandes, ATMI, Danbury, CT.

Delta doping (paused growth doping) was investigated as an alternative to uniformly distributing the dopant in the nitride semiconductor layer. Delta doping may offer a pathway to improved electronic and optoelectronic device performance through improved carrier concentration, carrier transport and other device properties. In this work, delta doped layers were produced in MOVPE-grown AlGaN and GaN layers by turning off the group III precursors (TMG and TMA) and introducing into the reactor a silicon precursor (disilane) for a fixed period (pause time) before growth was restarted. The electrical and compositional properties as a function of aluminum content, dopant flux and pause time were investigated for nitride layers on 2 inch c-plane sapphire substrates. Room temperature Hall mobility as high as 250 cm^2 V^{-1} s^{-1} for a sheet charge of 8×10^{12} cm^{-2} was demonstrated for delta-doped $Al_{0.25}Ga_{0.75}N$ layers, but the mobility enhancement saturated and then decreased with increasing sheet charge. Room temperature sheet charge increased with increasing pause time and dopant flux for delta doped AlGaN and GaN layers. Sheet charge density as high as 1.5×10^{13} cm^{-2} and 1.3×10^{13} cm^{-2} was measured at room temperature for $Al_{0.25}Ga_{0.75}N$ and GaN delta doped layers, respectively. Under identical doping conditions, the sheet charge of the delta doped $Al_{0.25}Ga_{0.75}N$ layer was approximately half as large as GaN layers. Secondary ion mass spectroscopy (SIMS) measurements revealed a sharp silicon peak with a FWHM of 60 angstroms for a sample that had a sheet charge of 7.9×10^{12} cm^{-2}. A detailed discussion of the electrical and impurity characteristics of the AlGaN and GaN delta-doped structures will be presented.

L11.45
AlGaN/GaN HFETS FOR AUTOMOTIVE APPLICATIONS. Ronald Birkhahn, David Gotthold, Nathan Cauffman, Boris Peres, EMCORE Corporation, Somerset, NJ; Seikoh Yoshida, The Furukawa Electric Co., Okano, Nishi-ku, Yokohama, JAPAN.

AlGaN/GaN heterojunction field effect transistors (HFET) on sapphire substrates have demonstrated ability as power devices operating with high current densities and high breakdown voltages. Additionally, AlGaN/GaN HFET devices have a very low on-state resistance. This makes these devices ideal for automotive applications such as switching relays, DC-DC converters, and power inverters. By 2006, switching devices using GaN-based FETs are anticipated to be employed in luxury automobiles and transitioned to the mass market by 2009. In this presentation, data from AlGaN/GaN HFETs grown in an Emcore D180 MOCVD system will be presented. Typical production-scale results (on 2" sapphire substrates) for these wafers were: $\mu \sim 916$ cm^2/V·s, $N_s = 1.74 \times 10^{13}$ cm^{-2}, and $R_s \sim 358$ Ω/sq. with <3% variation across the wafer. These wafers were then processed into devices using Pt/Au gate contacts with 2 μm gate length, 400 μm gate width, and a source to drain spacing of 13 μm. A total of 500 FETs were combined in parallel for an effective gate width of 20 cm for high current operation (10 Amps). These devices have a lower on-state resistance (<0.01 Ω-cm^2) and higher Schottky breakdown voltages (>500 V) than the theoretical limit of Si MOSFET devices. These devices are suitable for insertion in automotive electrical harnesses.

L11.46
LOW FREQUENCY NOISE IN AlGaN/InGaN/GaN DOUBLE HETEROSTRUCTURE FIELD-EFFECT TRANSISTORS. Nezih Pala, Sergey Rumyantsev, Michael Shur, Rensselaer Polytechnic Inst, Dept of Electrical, Computer, and Systems Engineering, Troy, NY; Remis Gaska, Xuhong Hu, Sensor Electronic Technology, Inc., Latham, NY; Jinwei Yang, Grigory Simin, Asif M. Khan, Univ of South Carolina, Dept of Electrical and Computer Engineering, Columbia, SC.

Group-III Nitride Heterostructure Field Effect Transistors (HFETs) have demonstrated impressive results in high frequency and high power electronics. Recently novel high power and current collapse free AlGaN/InGaN/GaN Double Heterostructure Field-Effect Transistors (DHFETs) have been reported. In this paper, we present experimental data on the low-frequency noise in AlGaN/InGaN/GaN heterostructures. Noise measurements on the TLM structures showed that the contact contribution to the noise is negligible compared to the channel. Both 1/f and generation recombination noise were observed in DHFETs. The amplitude of the 1/f noise was characterized by Hooge parameter $\alpha > 1 \times 10^{-4}$. These values of α are comparable with the best values reported for regular AlGaN/GaN HFETs. The temperature dependence of the measured noise spectral density has a wide and pronounced maximum at elevated temperatures. The temperature corresponding to the noise maximum increases with frequency. This dependence is typical for the generation-recombination noise caused by a local level. The activation energy for the generation-recombination noise extracted from the Arrhenius plots is ~1.6 eV. This is the largest reported activation energy for GaN based devices. From the capacitance voltage measurements combined with noise and dc measurements the dependences of the electron mobility and Hooge parameter α on 2D electron concentration in the channel were extracted. Both characteristics indicate better electron confinement in comparison with regular AlGaN/GaN HFETs.

L11.47
SUBBAND ELECTRON PROPERTIES OF MODULATION-DOPED *$Al_xGa_{1-x}N/GaN$* HETEROSTRUCTURES. D.R. Hang, C.F. Huang, Y.H. Chang, Y.F. Chen, National Taiwan Univ., Dept. of Physics, Taipei, TAIWAN; B. Shen, Nanjing University, National Laboratory of Solid State Microstructures and Dept. of Physics, Nanjing, CHINA.

We report an investigation of electronic properties of two-dimensional electron gas (2DEG) confined at *AlGaN/GaN* heterostructures by magnetotransport measurements. The second subband population is manifested by the multi-frequencies in the Shubnikov-de Haas oscillations (SdH). The modulated pattern of SdH oscillations due to multi-frequencies can be drastically enhanced by employing the microwave modulation technique. We provide direct experimental evidence that the 2DEG in the second subband has higher mobility that than in the first subband in the modulation-doped *$Al_{0.22}Ga_{0.78}N/GaN$* heterostructure by means of microwave-modulated magnetotransport measurements. The carrier concentrations, 2DEG Fermi energy and quantum mobilities for each subband were determined. It was found that the second subband population ratio increases with spacer thickness up to 5 nm, while the subband separation decreases.

L11.48
PHOTOREFLECTANCE AND PHOTOLUMINESCENCE OF A TWO-DIMENSIONAL ELECTRON GAS AT A GaN/AlGaN HETEROINTERFACE. Tomasz J. Ochalski, Lukasz Macht, Andrzej Grzegorczyk, Paul R. Hageman, Poul K. Larsen, Experimental Solid State Physic III, RIM, University of Nijmegen, Nijmegen, THE NETHERLANDS; Anna Wojcik, Tomasz Piwonski, Maciej Bugajski, Institute of Electron Technology, Warsaw, POLAND.

High quality GaN/AlGaN High Electron Mobility Transistor (HEMT) structures have been grown by metalorganic chemical vapor deposition

on sapphire (0001) substrates. All structures were unintentionally doped and a two-dimensional electron gas (2DEG) was formed at the AlGaN/GaN interface. Each sample consisted of 3μm thick base GaN layer on which a 200 nm AlGaN films with Al content varying between 10% and 30% were deposited. The formation of 2DEG at the AlGaN/GaN interface has been verified by photoreflectance (PR) and Capacitance Voltage (CV) analysis. For the best samples ground and excited states of 2DEG at the interface have been observed in PR spectra. The main characterization method used to evaluate the overall quality of the structures was photoluminescence (PL). We have used the 266 nm line from pulsed Nd:YAG laser as an excitation source. Room temperature measurements provided information about the exact Al content in AlGaN. All the above mentioned characterization methods were used to validate the quality of growth process of device structures. We demonstrate that discussed methods allow for fast and reliable selection of transistor structures, which are useful for high frequency and high current applications. Further advances in the performance of GaN based HEMTs are expected to occur with improvement in material quality.

L11.49
MONTE-CARLO SIMULATION OF SCATTERING ELECTRON TRANSPORT MECHANISMS IN GaN. Alexander Tamelo, Vladimir Muravév, Valery Mishenko, Dept of Radioelectronics, Minsk, BELARUS.

We assume that all donors are ionized and that the free electron concentration is equal to the dopant concentration. The scattering mechanisms considered are: a) ionized impurity, b) polar optical phonon, c) piezoelectric, d) acoustic deformation potential, and e) intervalley scattering between non-equivalent valleys. In each simulation, the motion of 6000 electrons is considered for the temperature T = 300 K, and the initial electron distribution is set according to equilibrium Fermi-Dirac statistics. In our investigations we ascribe an effective mass equal to the free electron mass to all of the upper conduction band valleys. We examine the results of our Monte Carlo simulations of electron transport in the GaN semiconductor. Specifically, we examine transient electron transport effects in the bulk GaN semiconductor for a variety of applied electric field strengths. In particular, we study how electrons, initially in equilibrium, respond to the sudden application of a constant applied electric field. Summed dependence of electron scattering frequency is calculated in wide energy range. These dependencies are presented for small energy E less 1 eV and for large energy E more 1 eV. It was determined that for energy level E less 1 eV only ionized impurity, polar optical phonon and acoustic deformation scattering mechanism are involved. The drift electron velocity and energy dependencies calculated for the electric field F = 10 kV/ cm are presented. The next parameters were used in the simulations: equilibrium concentration Cn = 1 10 17 cm-3, time interval increment t = 1 10-14 c. Calculation performed for energy E above 70 kV/cm are shown that character of the optical scattering is change in comparison to the optical scattering for the small energy. Phonon scattering for large energy values are completed in the narrow space angle and value of this angle closely equal to 0. While our Monte Carlo simulations of transient electron transport in the GaN semiconductor were made for different values of electric field, such calculations are computationally demanding. The one-dimensional energy-balance approach which employs steady-state Monte Carlo results appears to be easy to implement. This approach was originally suggested by Shur and was later adopted by others. This approach employs two coupled differential equations, one for energy relaxation and one for momentum relaxation. The obtained dependencies give the possibility to define frequency momentum time and energy relaxation time dependencies. It is permitted to calculate boundary ft for GaN transistors. Obtained values of relaxation frequencies are permitted to define the parameters of the HEMT using Boltzman equation and two-dimentional model. Studies of the electron transport in the two-dimensional electron gas formed at an AlGaN/GaN interface have also been performed.

L11.50
ELECTRICAL AND STRUCTURAL CHARACTERIZATION OF METAL CONTACTS ON GALLIUM NITRIDE. Annalisa Bonfiglio, Elisabetta Macis, Giovanna Mura, Univ of Cagliari, Cagliari, ITALY.

We have aimed to characterize metal-semiconductor contacts in GaN by means of several techniques, to assess, at the same time, the electrical and structural properties of the contact, and, where possible, their correlation. The problem is crucial in view of the realization of electronic devices of whatever kind. Therefore we addressed both the questions of obtaining good quality ohmic contacts, as well as that of measuring the barrier height of Schottky contacts. To this aim, we derived the electrical properties by measuring Capacitance vs. Voltage and Current vs. Voltage curves. At the same time, as we were particularly interested in the correlation between electrical parameters and structural features of the metal-semiconductor junction, we performed a SEM investigation and, in particular, we employed the method known as Electron Beam Induced Current (EBIC). EBIC is a technique that allows to measure, with the resolution allowed by SEM, the efficiency of a rectifying junction, if it is not too deep with respect to the scanned surface. In the case of metal-seconductor rectifying contacts, it was possible to obtain current maps which, complemented with the information obtained by SEM topographies, allowed to correlate the electrical efficiency of junctions with their structural characteristics. The experimental conditions of realization of the contacts were crucial: we have investigated several metals and several deposition conditions for the same metal (e.g., with and without post-evaporation annealing). The rationale was to verify, in the case of GaN, the well-assessed theories about the dependence of barrier height on work functions differences between metals and semiconductors as well as the correlation between barrier height and ionicity of the semiconductor, and, furthermore, to fully take into account also the role of technological issues in determining the final behaviour and reproducibility of the contacts.

L11.51
A STRUCTURAL ANALYSIS OF THE Pd/GaN OHMIC CONTACT ANNEALING BEHAVIOR. P. Ruterana, ESCTM-CRISMAT, UMR6508-CNRS, ISMRA Caen, FRANCE; C.C. Kim, Y.B. Kwon, J.H. Je, Synchrotron Xrays Laboratory, Department of Materials Science and Engineering, Pohang University, Pohang, SOUTH KOREA.

For ohmic contact on p GaN, palladium is one of the best candidates as it shows ohmic characteristics already without annealing. Although palladium (111) has been shown to adopt epitaxial relationships on top of the (0001) GaN surface, there is little information on the behavior at high temperature. For high power applications, it is necessary to know the behavior of the ohmic contacts. Therefore, we have studied the structural evolution of palladium layers (30 nm) deposited on GaN (0001) by electron beam evaporation without intentional annealing. They were next cut into various pieces and individually submitted to rapid thermal annealing at 400, 500, 600, 700 and 800°C for sec. We report on the different interfacial phases and their relationships as determined at atomic scale using high resolution electron microscopy and microanalysis (EDS, GIF).

L11.52
SYNCHROTRON PHOTOEMISSION STUDY OF OXIDIZED Ni/Au CONTACT ON p-TYPE GaN. Ho Won Jang, Chang Min Jeon, Jong-Lam Lee, Dept of Materials Science and Engineering, Pohang University of Science and Engineering (POSTECH), Pohang, KOREA.

The metal-GaN contact for low contact resistivity is a challenge in GaN-based optoelectronic and high power devices. The precise understanding of contact formation mechanisms for ohmic contacts on GaN is essential to improve the performance of the devices. Especially, the mechanism of an oxidized Ni/Au contact on p-GaN is not clear and still debating. In this work, the structural and electrical properties of both metallic and oxidized Ni/Au contacts on p-GaN were investigated using synchrotron photoemission spectroscopy. As-deposited Ni(2 nm)/Au(3 nm) contacts were annealed in N_2 and O_2, separately. The Ga, N, O, and C core levels, valence band, and secondary electron emission spectra were acquired. After annealing at 500°C in O_2, the Ni contact layer was perfectly transformed to a surface NiO layer, resulting in the contact structure of NiO/Au/p-GaN. Shifts in valence band and secondary electron emission edges indicated that the surface NiO layer is a degenerated p-type semiconductor. Compared to the Ni/Au contact annealed in N_2, Ga outdiffusion was more significant in the Ni/Au contact annealed in O_2, which could lead to the reduction of contact resistivity via an increase in the hole concentration of p-GaN near the surface.

L11.53
EFFECTS OF SURFACE TREATMENT USING THIOACETAMIDE SOLUTIONS ON Pt/Au OHMIC CONTACTS TO P-TYPE GaN. Suk-Ho Cho, June-O. Song, and Tae-Yeon Seong, Kwangju Institute of Science & Technology, Dept of Materials Science & Engineering, Kwangju, KOREA.

High quality ohmic contacts are crucial for improving the performance of optical devices. To obtain low resistance ohmic contacts to p-GaN, surface treatments using various chemical solutions such as KOH, HNO_3):HCl, and buffered oxide etch (BOE) have been performed. Our group showed that the two-step surface treatment with BOE is very effective in removing the native oxide and causes an increase of the carrier concentration at the surface region, resulting in a large reduction in the specific contact resistance. It was also shown that the surface treatments with alcohol-based $NH_4S_(x)$ solutions results in an improvement of the ohmic contact property. We showed that sulfide treatment using CH_3CSNH_2/NH_4OH solution results in a large reduction of the specific contact resistance of Ti/Al ohmic contacts to n-GaN. In this work, we investigate the passivation effects of [CH_3CSNH_2-based solutions (KOH, [CH_3CSNH_2 + KOH], and

[CH_3CSNH_2 + DI water] on Pt/Au ohmic contacts to p-GaN (n_a = $2x10^{17}$ cm^{-3}). It is shown that the sulfide treatment results in an increase in the photoluminescence intensity, compared with that of the untreated sample. Current-voltage (I-V) results show that the sulfide treatments using various solvents effectively improve the electrical properties of the contacts (which were measured using the TLM method), although the electrical properties are dependent upon the chemical solutions used. The specific contact resistance ranges from $\sim 10^{-2}$ Ωcm^2 for the untreated sample to $\sim 10^{-4}$ Ωcm^2 for the treated samples. It is also shown that annealing of the sulfide-treated sample (at 600°C in a nitrogen atmosphere) results in a further improvement in the specific contact resistance ($\sim 10^{-5}$ Ωcm^2). X-ray photoemission spectroscopy (XPS) was employed to investigate ohmic behaviours of the surface-treated Pt/Au contacts to p-GaN. Based on the I-V and XPS results, the sulfide and annealing treatment dependence of the specific contact resistance is discussed.

L11.54
Ti/Al- GaN INTERFACE ANALYSIS FOR LOW CONTACT RESISTANCE FORMATION. Yoshimichi Fukasawa, Tomonori Nakamura, Tohru Nakamura, College of Engineering, Hosei University, Tokyo, JAPAN.

Ti/Al metal is commonly used for ohmic contacts to n-GaN. Interface analysis for Ti/Al metal is important to form low ohmic resistance electrodes. An n-GaN layer with a carrier concentration of $2.17x10^{18}$ cm^{-3} on sapphire substrate was used. Ohmic contacts were made with Ti thickness ranging from 200 Å to 800 Å for 1000 Å -thick Al, and with Al thickness ranging from 500 Å to 1500 Å for 500 Å-thick Ti. Annealing was carried out at 900 °C for 3 min. Contact resistivity decreased as the Ti thickness increased, and increased as the Al thickness decreased. The lowest contact resistivity was measured at $1.20x10^{-6}$ Ωcm^2 for 800 Å Ti /1000 Å Al. 1.5 MeV Rutherford Backscattering Spectroscopy (RBS) was used to clarify the interface between Ti/Al and n-GaN layer. It was found that Al/AlTi/TiN/GaN layers were formed and that the reacted thing of Ti and Al decreased as Ti increase, after annealing. We also found that the reaction of Ti and GaN was largest at 800 Å Ti /1000 Å Al, and contact resistivity as low as $3.02x10^{-7}$ Ωcm^2 was obtained for the Ti thickness of 1000 Å without Al layer. From these results, we conclude that contact resistivity depends upon the thickness of Ti/GaN alloy.

L11.55
COMPARATIVE MORPHOLOGY OF AuTiAlTi, AuPdAlTi AND AuAlTi OHMIC CONTACTS TO AlGaN/GaN. M.W. Fay, G. Moldovan, P.D. Brown, School of Mechanical, Materials, Manufacturing Engineering and Management, University of Nottingham, Nottingham, UNITED KINGDOM; I. Harrison, School of Electrical and Electronic Engineering, University of Nottingham, Nottingham, UNITED KINGDOM; R.S. Balmer, K.P. Hilton, B.T. Hughes, M.J. Uren, T. Martin, QinetiQ Ltd, Malvern, Worcs, UNITED KINGDOM.

AuTiAlTi, AuPdAlTi and AuAlTi ohmic contacts to AlGaN/GaN rapid thermal annealed at temperatures up to 950°C have been analysed using conventional and chemical transmission electron microscopy characterisation techniques. The relationship between the as-deposited structure, annealing temperature, post-anneal interfacial microstructure and contact resistance is examined. In particular, the effect of a Pd or Ti barrier layer between the Au and Al, with implications for the diffusion of Au to the nitride/contact interface, is compared to samples with no barrier metal used. Consumption of the AlGaN layer and the formation of Ti-Nitride interfacial grains and inclusions are described. The implications for electrical coupling of the active region and contact are discussed.

L11.56
THERMAL STABILITY OF TaN SCHOTTKY CONTACTS ON n-GaN. J.R. Hayes, D.W. Kim, H. Meidia, S. Mahajan, Arizona State University, Dept. of Chemical and Materials Engineering, Tempe, AZ.

The thermal stability and electrical characteristics of TaN Schottky contacts on n-GaN were investigated. Transmission electron microscopy studies on TaN/GaN samples annealed to temperatures as high as 800°C revealed a stable interface with few microstructural changes. Current-voltage and capacitance-voltage electrical measurements were performed on samples annealed up to 800°C. The electrical performance of the contacts did not significantly change on annealing. The TaN Schottky contacts had an I-V barrier height near 0.7 eV and a C-V barrier height near 1.2 eV. The ideality factors were above 1.8 at all annealing temperatures, suggesting tunneling contributes significantly to current transport. The microstructural and electrical stability of the TaN/GaN interface stems from the thermodynamic stability of the system.

L11.57
STABLE OHMIC CONTACTS ON GaAs AND GaN DEVICES FOR HIGH TEMPERATURES. A. Piotrowska, E. Kaminska, K. Golaszewska, H. Wrzesinska, T.T. Piotrowski, Institute of Electron Technology, Warsaw, POLAND; A. Barcz, E. Dynowska, R. Jakiela, A. Wawro, Institute of Physics PAS, Warsaw, POLAND.

The development of high power/high temperature electronics imposes more stringent requirements on the thermal stability of interfaces between semiconductor and contact metallization. Transition metal nitrides, presenting an exceptional combination of properties like low resistivity, high melting point and resistance to corrosion, are considered as good candidates for thermally stable contacts. In this communication, we report on thermal stability of refractory metal nitride contacts to both, GaAs and GaN. Thin films of TiN, ZrN and NbN were chosen for this study. Both TiN and NbN films were deposited by reactive magnetron sputtering in Ar/N_2 atmosphere, from elemental Ti and Nb target, respectively. ZrN layers were prepared by RF sputtering from ZrN target. Heat treatments were performed in a rapid thermal annealer under flowing N_2. We investigate the evolution of contact microstructure under heat treatment at temperatures up to 1200°C and its effect on contact electrical properties. Microstructural analysis was performed using secondary ion mass spectrometry, x-ray diffraction, and atomic force microscopy. The electrical characterisation involved measurements of I-V characteristics for rectifying contacts and resistivity for ohmic contacts. We show that for GaAs, the highest thermal stability up to 900°C can be obtained by using NbN contacts. As for GaN substrates, both ZrN and NbN produced stable metallization upon annealing up to 1050°C. The obtained results suggest that the degradation of electrical properties under high thermal stress is related to the recrystallization of initially amorphous metallization.

L11.58
OHMIC AND RECTIFYING CONTACTS TO N AND P-TYPE GaN FILMS. H. Hall, M. Awaah, A. Kumah, K. Das, Tuskegee University, Dept. of Electrical Engineering, Tuskegee, AL; F. Semendy, Army Research Laboratory, Adelphi, MD.

Electrical contacts to both n and p-type GaN films have been investigated using electron-beam evaporated and sputtered films of metals such as Al, Au, Cr, Cu, Ni, Pt, and Ti. Films deposited by electron-beam evaporation for the n-type films with doping levels of 1 x $10^{18}/cm^3$ and lower showed rectifying characteristics with all the metals studied with the exception of Al. Aluminum contact diodes were ohmic as-deposited. The Pt rectifying contact was near-ideal with an ideality factor close to 1.0. Ideality for the other metals were much greater than 1. However, carrier transport in these contact diodes, particularly at low biases, appeared to be dominated by space charge limited current as opposed to thermionic emission. Therefore, the use of an ideality factor based on the assumption that thermionic emission prevailed may not be justified. Sputtered films showed very similar characteristics as electron-beam deposited films, with the exception of Ti. The Ti contact was nearly ohmic in the as-deposited state. Non-linear Cu contacts to n-type films became ohmic on annealing. For p-type films most of the metal contacts showed highly non-linear current-voltage characteristics. However, for Ar ion bombardment prior to metal deposition by sputtering created nearly ohmic contacts with Cu and Pt. Low resistance ohmic contacts were achieved by ion implantation of Si in n-type and Mg in p-type films to a dose of 1 x $10^{15}/cm^2$ at 35 keV. These implants were annealed at 1100°C with a capping layer of SiO_2. Contact resistivities of the order of 1 x $10^{-7}\Omega \cdot cm^2$ for n-type films were obtained with deposited Ti/Au bilayers (annealed at 900°C) and ~1 x $10^{-5}\Omega \cdot cm^2$ with Ni/Au for p-type films (annealed at 550°C). The implant parameters and anneal temperatures are currently being optimized.

L11.59
ACTIVATION AND PASSIVATION OF Mg ACCEPTOR IN GaN:Mg. D. Matlock, M.E. Zvanut, Department of Physics, University of Alabama at Birmingham, Birmingham, AL; Jeffrey R. DiMaio, R.F. Davis, Department of Materials Science and Engineering, NCSU, Raleigh, NC; J.E. Van Nostrand, Materials and Manufacturing Directorate, AFRL, WPAFB, OH; R.L. Henry, NRL, Washington, DC; Daniel Koleske, Sandia National Laboratories, Albuquerque, NM; Alma Wickenden, U.S. Army Research Laboratory, Adelphi, MD.

Hydrogen removal from GaN:Mg is necessary to activate p-type conductivity, but the exact chemical process is not clear. We have investigated this issue by monitoring the intensity of an electron paramagnetic resonance (EPR) signal thought to be due to the Mg acceptor. For simple H depassivation of Mg, the acceptor resonance should be observed only after bond breakage, and the activation energy should reflect the Mg-H complex bond energy. Approximately 1 μm thick GaN films were deposited by Molecular Beam Epitaxy (MBE) or chemical vapor deposition (CVD) onto (0001) 6H SiC or sapphire substrates. EPR was performed at 4 K before and after annealing samples between 600 and 1000 °C for 1 hr in dry N_2 or 93%N_2:7%H_2. The Mg spectrum initially present in the MBE films

decreased by at least an order of magnitude after the 800 °C N_2:H_2 anneal and returned to approximately its original value after a 800 °C N_2 anneal. In CVD samples not subjected to p-type activation, N_2 annealing between 700 and 850 °C increased the signal intensity. The results from both types of films are consistent with depassivation of Mg by removal of hydrogen; however other observations suggest more complicated kinetics. The unactivated CVD films revealed a signal resembling the Mg acceptor that was quenched by a 650 °C N_2 anneal. In all samples, N_2 annealing at T > 850 °C irreversibly decreased the amount of activated Mg. Although the presence of the Mg-like signal in the as-grown films is not yet understood, the effects observed at T > 850 °C are thought to be related to N-desorption from Mg-H complexes. We will report annealing kinetics and activation energies obtained from dry N_2 anneals and compare these to values expected for various Mg complexes. This work is supported by the Office of Naval Research and the Air Force Office of Scientific Research.

L11.60
MICROSTRUCTURAL DEFECTS IN Mg-DOPED AlGaN LAYERS GROWN BY METALORGANIC CHEMICAL VAPOR DEPOSITION. Hyung Koun Cho, Dong-A University, Dept of Metallurgical Engineering, Busan, KOREA; Gye Mo Yang, Chonbuk National University, Dept of Semiconductor Science & Technology, Chunju, KOREA.

For good photon and current confinement, a low Al composition AlGaN cladding layer is used in the actual InGaN/GaN quantum well light emitting diode (LED) and laser diode (LD) structures. Also, planar defects such as stacking fault, inversion domain boundary (IDB), and stacking mismatch boundary are observed in GaN layers grown on sapphires, in addition to threading dislocations. It has been reported that the control of the polarity greatly affects the optical and structural properties of LED and LD devices. In this experiment, influence of Mg doping on structural defects in $Al_{0.13}Ga_{0.87}N$ layers grown on sapphire substrates by metalorganic chemical vapor deposition was studied using transmission electron microscopy. By increasing the Mg source flow rate, the reduction of dislocation density occurred up to the Mg source flow rate of 0.103 μmol/min. While the vertical type inversion domain boundaries (IDBs) were observed in the $Al_{0.13}Ga_{0.87}N$ layers grown with the low Mg source flow rate, the IDBs in the $Al_{0.13}Ga_{0.87}N$ layers grown with the high Mg source flow rate have horizontally multifaceted shapes. The change of polarity by the IDBs of horizontal type also resulted in the 180° rotation of pyramidal defects within the same AlGaN layer. Therefore, We found that the Mg source flow rate affects significantly the dislocation density, the type of IDBs, and the shape of pyramidal defects in AlGaN layers.

SESSION L12: CONTACTS, PROCESSING, AND p-TYPE NITRIDES
Chair: David C. Look
Friday Morning, December 6, 2002
Room 302 (Hynes)

8:30 AM *L12.1
ISSUES OF PREPARING OHMIC CONTACT MATERIALS FOR p-GaN. Masanori Murakami, Yasuo Koide, Miki Moriyama, Department of Materials Science and Engineering, Kyoto University, Kyoto, JAPAN.

Although extensive studies have been carried out to prepare reproducible ohmic contact materials for p-type GaN, the contact materials which provide both low contact resistances and excellent thermal properties (essential for both electronic and optoelectronic devices) have not yet been developed. However, a variety of ohmic contact materials which have the contact properties exceeding the manufacturing levels have been developed for other compound semiconductors These contact materials were primarily developed by correlating the electrical properties and the microstructures at the metal/semiconductor interfaces which were analyzed by using various techniques. In this talk we will discuss the possible reasons why the guidelines established by preparing ohmic contact materials for other compound semiconductors (such as GaAs, InP, ZnSe, SiC etc) are not directly applicable to the contact materials for p-type GaN. We will specially address the engineering issues of surface cleaning, heavy carrier doping from the contact materials to GaN, and reduction of the barrier height at metal/GaN interface by annealing at elevates temperatures. In addition, the contact properties observed in our laboratories peculiarly in GaN will be reviewed.

9:00 AM L12.2
OHMIC CONTACTS TO HIGH ALUMINUM FRACTION P-TYPE AlGaN. Brett A. Hull, Suzanne E. Mohney, Pennsylvania State University, Dept. of Materials Science and Engineering, University Park, PA; Uttiya Chowdhury, Russell D. Dupuis, University of Texas at Austin, Dept. of Electrical and Computer Engineering, Austin, TX.

With growing interest in very short wavelength emitters, ohmic contacts to the Al-rich nitride semiconductors have become an important problem. Ohmic contacts to p-type $Al_xGa_{1-x}N$ with x = 0.45 have been investigated in this study. Single layer contacts of Pd, Pt, Ni, or Au were deposited by electron beam evaporation. As deposited, the Pd and Pt contacts showed nearly linear I-V characteristics, while the Ni and Au contacts were somewhat more rectifying. The apparent contact resistivity ranged from 4.8 ± 0.5 $\Omega\cdot cm^2$ for the Pt contacts to 54 ± 6 $\Omega\cdot cm^2$ for the Ni contacts (calculated using the circular transfer length method and a measurement current of 10^{-5} A). Following annealing at 500 to 650°C for 2 min, the contacts became rectifying and very resistive, with the exception of the Pt contacts, which showed only minor degradation. With subsequent annealing at greater than 700 to 750°C for 2 min, the contacts improved greatly, with linear I-V curves and a minimum contact resistivity of $1.8 \times 10^{-3} \pm 1.1 \times 10^{-3}$ $\Omega\cdot cm^2$ for the Au contacts annealed at 850°C. However, for the Pt, Pd, and Au contacts annealed at 750°C or greater, a rapid photo-induced increase in the resistance of the contacts and semiconductor was observed. In these three samples, within 15 min of exposure to white light, the contact resistivity degraded up to three orders of magnitude to near their as-deposited values. No degradation was observed for the Ni contacts, but the electrical properties of these annealed contacts were initially far inferior to those of the other three metals. Characterization is underway to investigate both the mechanism of the photo-induced degradation as well as the metal/AlGaN interfacial reactions that correlate with the significant drop in contact resistivity with the annealing of some metals above 750°C.

9:15 AM L12.3
BURIED STRESSORS IN NITRIDE SEMICONDUCTORS: INFLUENCE ON ELECTRONIC PROPERTIES. P. Waltereit, A.E. Romanov[a], and J.S. Speck, Materials Dept., University of California, Santa Barbara, CA. [a]also, Ioffe Institute, St. Petersburg, RUSSIA.

The distinguishing properties of nitride semiconductors include their lattice mismatches with respect to each other and polarization-induced electrostatic fields of a magnitude not found in other III-V semiconductors. These phenomena have a large impact on electronic properties of nitride semiconductors as they modify the conduction and valence band levels and also lead to electrostatic fields due to polarization charges. We investigate the influence of the strain field originating from a subsurface quantum dot on the electronic properties of nitride semiconductors. The material surrounding the quantum dot is considered either to be a uniform GaN matrix or a GaN/(In,Ga)N/GaN single quantum well. Isotropic elasticity is used to calculate the strain field around the quantum dot, which was modeled as a point dilatation stressor or an ellipsoidal inclusion. A k·p perturbation theory approach is applied to examine the shifts of the conduction and valence band edges caused by the stressor. We find substantial changes (of the order of 10 meV) in the valence and conduction band levels leading to the confinement for electrons and holes, which can be utilized to realize a strain-induced quantum dot in the single quantum well. The spatial variation of the polarization field is obtained by summing the spontaneous polarization and piezoelectric polarization, where the latter is obtained directly from the stressor elastic strains and piezoelectric coefficients of GaN. For typical stressors (quantum dots) in nitride semiconductors, the magnitude of polarization charge density is of the order 1016-1017 e cm-3. It is shown that the distribution of polarization charges induced by subsurface stressors in nitride semiconductors exhibits the rotational symmetry about the axis normal to the sample surface. This finding is due to the properties of GaN piezoelectric tensor and it is in contrast to the case of a stressor in zincblende crystals where the polarization charge density demonstrates a two-fold quadrupole-like symmetry.

9:30 AM L12.4
GaN MICRODISK FABRICATION USING PHOTO-ELECTROCHEMICAL ETCHING. E.D. Haberer, A. Stonas[a], Y. Gao, S. DenBaars, E.L. Hu[a], Materials Department, University of California, Santa Barbara, CA; [a]Dept. of Elect. and Comp. Eng., University of California, Santa Barbara, CA.

The geometry of the microdisk is ideal for studying the microcavity effects in a material system such as GaN in which cleaved facets and several period epitaxial mirror stacks are problematic. A microdisk is a thin semiconductor disk surrounded by a lower index material. The circular geometry of the disk and large index difference between the disk and the surrounding material allow low loss whispering gallery modes (WGMs) to propagate around the disk periphery through total internal reflection. Although microdisks have been fabricated in several III-V semiconductor systems, GaN microdisk development has been hindered by a lack of suitable processing techniques. Two main approaches have been used thus far. The first approach (taken by

J.W. Lee et al.[1]) mimicked the mushroom-like shape used frequently in the GaAs- and InP-based systems by using KOH to selectively etch an AlN pedestal. Although this method produced the appropriate mushroom-shaped structures, the technique was problematic because the selectivity of AlN was material quality dependent. The second approach (taken by R.A. Mair et al.[2]) took advantage of the lower index sapphire substrate, n = 1.8, by growing a thin (< 0.5 micron) layer of GaN-based material on sapphire and patterning it will a subsequent dry etch step. This approach was more successful, however the material quality of initial GaN growth may have limited disk performance. In this study, we have developed a new means of processing GaN-based microdisks through the use of photoelectrochemical (PEC) etching. We use an epitaxial structure grown by MOCVD which includes an InGaN sacrificial layer. RIE is used to define micropillars ranging from 2-9 microns in diameter and expose the InGaN sacrificial layer. The GaN microdisks are undercut by using bandgap selective PEC etching to etch the InGaN sacrificial layer. This study explores the optical emission of GaN and InGaN/GaN microdisks. [1]J.W. Lee, C.B. Vartuli, C.R. Abernathy, J.D. MacKenzie, J.R. Mileham, S.J. Pearton, R.J. Shul, J.C. Zolper, M. Hagerott-Crawford, J.M. Zavada, R.G. Wilson, and R.N. Schwartz, Journ. Vac. Sci. Technol. B 14, 3637 (1996). [2]R.A. Mair, K.C. Zeng, J.Y. Lin, H.X. Jiang, B. Zhang, L. Dai, H. Tang, A. Botchkarev, W. Kim, and H. Morkoc, Appl. Phys. Let. 71, 2898 (1997).

9:45 AM L12.5
ION SENSITIVE FIELD EFFECT TRANSISTORS BASED ON AlGaN/GaN HETEROSTRUCTURES. Martin Eickhoff, Georg Steinhoff, Martin Hermann, Martin Stutzmann, Walter Schottky Institute, Technical University Munich, Munich, GERMANY.

Recently, group III-nitrides have been shown to bear a great potential for the realization of different kinds of sensors. The piezoresistive effect in GaN and AlGaN layers has been shown to allow the realization of mechanical sensors [1,2]. Also chemical sensors based on Pt:GaN Schottky diodes [3,4], which can detect hydrogen and hydrogen containing gases up to temperatures of 600°C [5], have been demonstrated. The electronic properties of AlGaN/GaN heterostructures, which form a polarization induced two-dimensional electron gas at the heterointerface [4], are highly sensitive toward changes of the surface charge or the surface potential [6]. In combination with the chemical inertness of this material system, the design of ion sensitive field effect transistors (ISFETs) based on AlGaN/GaN heterostructures is a promising approach for the application as chemical sensors in aqueous solutions such as biosensors or pH sensitive devices. We have investigated the performance of ISFETs based on AlGaN/GaN heterostructures in electrolyte solutions with different ion concentrations and pH-values. The material properties of the ion sensitive gate area, which is exposed to the aqueous solution, turned out to have significant influence on the sensitivity and the stability of the device. ISFETs with different gate passivations, as Al_2O_3, SiO_2 or Si_3N_4, have been analyzed and the influence the gate passivation layer in the ISFET performance is discussed. AlGaN/GaN ISFETs with unpassivated gate area were found to degrade when operated in aqueous electrolyte solutions. This degradation results in a permanent depletion of the conducting channel and can be partially recovered by irradiation with UV-light or vacuum annealing. The underlying degradation mechanisms have been investigated by spectral resolved photocurrent measurement, thermally stimulated desorption and XPS analysis. [1]: M. Eickhoff, O. Ambacher, G. Krötz, and M. Stutzmann, J. Appl. Phys. 90, 3383 (2001) [2]: A.D. Bykhovski, V.V. Kaminskii, M.S. Shur, Q.C. Chen, and M.A. Khan, Appl. Phys. Lett. 68, 818 (1996) [3]: B.P. Luther, S.D. Wolter, S.E. Mohnley, Sensors and Actuators B 56, 164 (1999) [4]: J. Schalwig, G. Müller, U. Karrer, M. Eickhoff, O. Ambacher, M. Stutzmann, L. Görgens, G. Dollinger, Appl. Phys. Lett. 80, 1222 (2002) [5]: J. Schalwig, G. Müller, U. Karrer, M. Eickhoff, O. Ambacher, M. Stutzmann, Mat. Sci. Eng. B (2002), in print [6]: R. Neuberger, G. Müller, O. Ambacher, M. Stutzmann, phys. stat. sol (a) 185, 85 (2001).

10:30 AM *L12.6
SUBSTITUTIONAL AND INTERSTITIAL CARBON IN WURTZITE GALLIUM NITRIDE. A.F. Wright and C.H. Seager, Sandia National Laboratories, Albuquerque, NM; J. Yu and W. Goetz, Lumileds Lighting, San Jose, CA.

Residual C is often present in GaN films grown via metal-organic vapor phase epitaxy (MOVPE) with possible sources including hydrocarbon fragments from the metal-organic compound, CO and CO_2 contaminants in the NH_3 supply, and hydrocarbons resulting from H_2 etching of the SiC coated graphite susceptor used to inductively heat the substrate. C is expected to be an acceptor when substituting for N, and experimental and theoretical studies indicate that C is, in fact, a shallow acceptor in this configuration. Attempts to produce p-type C-doped GaN, however, have achieved only limited success, and results obtained from material grown using molecular beam epitaxy (MBE) suggest that the low C doping efficiency may be due to self-compensation. In order to develop a better understanding of C in GaN, we have performed theoretical and experimental studies for this system. The theoretical study examined both substitutional and interstitial C. The results indicate that C is a shallow acceptor when substituting for N (C_N) and a shallow donor when substituting for Ga (C_{Ga}). Interstitial C (C_I) assumes different configurations depending on the Fermi level: A site at the center of the wurtzite c-axis channel is favored when the Fermi level is below 0.9 eV (relative to the valence band maximum) and a split-interstitial configuration is favored otherwise. Both C_{Ga} and C_I are predicted to be donors in p-type GaN and may therefore self-compensate C_N acceptors. Channel-centered C_I is predicted to the the primary self-compensating species when growth occurs under Ga-rich conditions and C_{Ga} is predicted to be the primary self-compensating species under N-rich growth conditions. The former result is consistent with the experimental results from MBE material noted above, while the latter is consistent with our own experimental studies on Si-doped MOVPE material intentionally co-doped with C. These samples were observed to undergo a transition from n-type conducting to insulating as the C concentration was increased relative to a fixed Si concentration, and a 3.0 eV cathodoluminescence peak seen in the insulating samples was attributed to electronic transitions between the C_{Ga} donor state and the C_N acceptor state. We also present theoretical results for H in C-doped GaN. This work was partially supported by the Office of Basic Energy Sciences, U.S. Dept. of Energy. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Dept. of Energy under Contract DE-AC04-94AL85000.

11:00 AM L12.7
STRUCTURAL DEFECTS IN Mg DOPED GaN AND AlGaN GROWN BY MOCVD. S. Tomiya, Material Analysis Dept., Technical Solutions Center, Sony Corporation, Yokohama, JAPAN; S. Goto, M. Takeya, M. Ikeda, Sony Shiroishi Semiconductor Inc., Miyagi, JAPAN.

Minimizing power consumption of LDs is critical important for extending the device lifetime [1]. One of the key issues is optimization of the Mg doping conditions to GaN and AlGaN layers in order to lower resistivity. During the course of our study of LDs, inverse pyramidal shaped defects (which are referred simply as "efects" hereafter) are often found in Mg-doped layers by transmission electron microscope (TEM) observations. The defects may increase resistivity of the p-type layers; therefore, these should be eliminated. Recently, the defects have been reported by several researchers [2-4], however, formation mechanism of the defects is not yet fully understood. In this paper, we have investigated relation between formation of the defects and Mg atomic concentrations [Mg]. Samples grown by MOCVD are characterized using TEM and secondary ion mass spectroscopy. The defects in GaN and AlGaN are appeared when the [Mg] are not lower than $5x10^{19}/cm^3$. Although the size of the defects strongly depends on the growth conditions, the following features are summarized; Their size are not larger than 15 nm. The density of the defects are increased when the [Mg] are increased, however, the size of the defects becomes smaller when the [Mg] are increased. The density of the defects is 1-2 order lower than the [Mg]. The defects in GaN are smaller than that in AlGaN when the [Mg] are the same. Based on above results, diffraction contrast analysis, lattice image analysis and strain field analysis, we discuss the formation mechanisms of the defects. [1] T. Tojyo, et al. Jpn. J. Appl. Phys. 40, 3206 (2001) [2] Z. Liliental-Weber, et al., Appl. Phys. Lett., 75, 4159 (1999) [3] P. Vennéuès, et al., Appl. Phys. Lett., 77, 880 (2000) [4] M. Hansen, et. al. Appl. Phys. Lett., 80, 2469 (2002)

11:15 AM L12.8
INFLUENCE OF AMBIENT ON SURFACE-INHIBITED H RELEASE FROM p-GaN. S.M. Myers, W.R. Wampler, C.H. Seager, B.L. Vaandrager, D.D. Koleske, A.A. Allerman, Sandia National Laboratories, Albuquerque, NM; J.S. Nelson, Uniroyal Optoelectronics, Tampa, FL.

We previously reported that H release from MOCVD-grown, Mg-doped GaN during high-vacuum annealing is strongly retarded by a surface-barrier effect, characterized by second-order kinetics consistent with recombinative desorption of H2. Here we present results from an ongoing mechanistic study of the influence of surface condition and ambient on the release, with investigated conditions including 1) UHV with sputtering and annealing to produce clean, ordered surfaces as shown by Auger and LEED; 2) high-vacuum annealing with as-grown surfaces; and 3) N2 gas with varying additions of O2. During sequences of isothermal anneals, the bulk concentration of H is monitored by nuclear-reaction analysis and IR spectroscopy. In analyzing the results, the chemical potential and mobility of H within the semiconductor matrix are treated using a theoretical model validated by comparison with experimental measurements of equilibrium solubility and internal migration under bias, facilitating the separation and quantification of surface effects.

We find the barrier effects to be similar for as-grown surfaces during high-vacuum annealing and for clean, well ordered surfaces heated in UHV; the data accord with second-order desorption kinetics over more than two decades in bulk H concentration. The N2 ambient containing O2 causes a fundamental change in behavior, producing accelerated release that is consistent with first-order surface kinetics over more than two decades in bulk H concentration. Mechanisms under consideration include O-H reactions at the surface giving rise to volatile species. Measurements of the dependences on temperature and O2 concentration are underway and are expected to illuminate reaction paths and the associated activation barriers. This work was supported by the Office of Basic Energy Sciences, U. S. Department of Energy, under Contract DE-AC04-94AL85000.

11:30 AM L12.9
MEASUREMENTS AND MODELING OF H DIFFUSION IN P-TYPE GaN. C.H. Seager, S.M. Myers, A.F. Wright, D.D. Koleske, A.A. Allerman, Sandia National Laboratories, Albuquerque, NM.

Using capacitance-voltage measurements we have measured both the diffusion and the field-induced drift of H in GaN p/n^+ diodes grown by Metal Organic Vapor Phase Epitaxy (MOVPE). Our data is well described by a computational model which simulates all of the important electronic processes as well as the drift, diffusion, and trapping of hydrogen in the GaN lattice. The experimental data demonstrate conclusively that H exists in the positive charge state; they also suggest that hydrogen diffusivity is anisotropic in this hexagonal material. In the temperature range from 210-310°C we have determined that the sum of the activation energies for diffusion and binding of H^+ to magnesium acceptors is 2.0 eV. This is ~0.6 eV larger than previous theoretical estimates of this quantity. We present density functional calculations using both the local density and generalized gradient approximations to treat electron exchange and correlation. These demonstrate the observed diffusion anisotropy and better agreement with our experimentally determined barrier for hydrogen diffusive motion. This work was supported by the Basic Energy Sciences Office of the Department of Energy. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

11:45 AM L12.10
A WAFER-FUSED N-AlGaAs/P-GaAs/N-GaN HETEROJUNCTION BIPOLAR TRANSISTOR(HBT). Sarah Estrada, Andrew Huntington, Andreas Stonas, Larry Coldren, Steven DenBaars, Umesh Mishra, Evelyn Hu, Depts of Materials and Electrical & Computer Engineering, University of California, Santa Barbara, CA; Jacek Jasinski, Zuzanna Liliental-Weber, Materials Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA.

We describe the use of wafer fusion to form HBTs with an AlGaAs/GaAs emitter/base and a GaN collector. In this way, we hope to make use of both the high breakdown voltage of the GaN and the high mobility of the technologically more mature GaAs-based materials. Because the high degree of lattice mismatch between GaAs (lattice constant of 5.65A) and GaN (3.19A) precludes an all-epitaxial formation of this device, we fabricate the GaAs/GaN heterostructure via the novel technique of wafer fusion. The AlGaAs/GaAs emitter/base was grown by MBE. A sacrificial layer (0.5um) of undoped AlAs was grown on (100) n+GaAs substrate, followed by a contact layer (0.1um n+GaAs, 1e19 Si), the device emitter (0.18um graded nAlGaAs, 5e17 Si), and finally the device base (0.15um p+GaAs, 1e19 C). C, rather than Be, was chosen as the p-type dopant in order to minimize dopant diffusion during the high-temperature fusion procedure. The uid-GaN collector (nominal 5e16 Si) was grown by MOCVD on c-plane (0001) sapphire. The GaN and GaAs structures were fused together at systematically varied temperatures (500-750oC) for 1 hour under a uniaxial pressure of 2 MPa in a nitrogen ambient. After removal of the GaAs substrate and sacrificial AlAs, emitter (1e-5cm2) and base mesas (5e-5cm2) were defined. Emitter contacts were NiAuGe, base contacts were ZnAu, and collector contacts were AlAu. We will describe and analyze the IV characteristics of our HBT structures and correlate the electrical performance with the quality of the fused interface, given chemical information provided by SIMS and structural information from TEM analysis.